Geodynamic evolution of the SW Europe Variscides

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[1] The early evolution of SW Europe Variscides started by opening of the Rheic ocean at ~500 Ma, splitting Avalonia from Armorica/Iberia. Subduction on the SE side of Rheic generated the Paleotethys back-arc basin (430–390 Ma, splitting Armorica from Iberia), with development of Porto-Tomar-Ferreira do Alentejo (PTFA) dextral transform defining the boundary between continental Armorica and Finisterra microplate to the W. Obduction of Paleotethys was followed by Armorica/Iberia collision and emplacement of NW Iberian Allochthonous Units at 390–370 Ma, whereas toward the west of PTFA, there was antithetic ophiolite obduction (Beja-Acebuches and Rheic ophiolites plus Finisterra continental slices) on top of Ossa-Morena Zone, with simultaneous development of eclogites and orogenic magmatism under a flake–double wedge tectonic regime. Continued convergence (<370 Ma) proceeded by intracontinental deformation, with progressive tightening of the Ibero-Armorican Arc through dextral transpression on the Cantabrian Indentor, from Iberia to Armorica. The proposed model is discussed at the light of the driving mechanism of "soft plate tectonics." **Citation:** Ribeiro, A., et al. (2007), Geodynamic evolution of the SW Europe Variscides, *Tectonics*, *26*, TC6009, doi:10.1029/2006TC002058.

1. Introduction

[2] The purpose of this paper is to review the geodynamic evolution of the SW Europe Variscides on the basis of geological data, obtained mostly in Iberia. Recent data was made available following two main research lines. The first one embraced a multidisciplinary approach [*Ribeiro and Sanderson*, 1996], culminating with the acquisition and interpretation of a deep seismic reflection profile on the Spanish segment of the SW Iberia [*Simancas et al.*, 2003]. The second one was based on major geological syntheses at a regional level, both in Spain [*Vera*, 2004] and Portugal [*Dias et al.*, 2006], integrating stratigraphic, petrological, geochemical, geochronological and tectonic data with the analysis of the aforementioned SW Iberia deep seismic profile [*Simancas et al.*, 2003; *Carbonell et al.*, 2004]. On this basis, the geodynamic evolution of both Iberia and Armorica will be discussed within an updated global paleomagnetic framework in order to address the rationale of its integration on the larger context of the SW European Variscides. The proposed evolution complements and details interpretations based on data from Central and Eastern Europe Variscides [*Stampfli and Borel*, 2002]. Conceptual differences result mainly from the study of continuous transects from lower to upper crustal levels in SW Europe. These transects are not much affected by younger events such as the opening of the Atlantic and Tethys as well as the Alpine reworking of Variscan basement, contrasting with the situation in Central/Eastern Europe.

2. Geodynamic Setting: Role of Variscan and Cadomian Cycles

[3] There are two schools of thought about the geodynamic evolution of SW Europe Variscides that distinctly interpret the role of Variscan and Cadomian tectonics cycles to produce the present geological materials and structures. For some authors (referred below) the main geological events are Variscan; for others (including ourselves) the main Variscan geological events overprint relicts of a Cadomian (and pre-Cadomian?) cycle. This problem is significant in domains where major tectometamorphic events of the Variscan cycle reworked previous structures that can be either polyorogenic, in the sense that they record early stages of the Variscan cycle, or polycyclic, in the sense that they record relicts of an older Cadomian cycle. To address this issue an overview of the SW Europe Variscides geodynamics must be outlined, particularly in the orogenic domains where the new available data can lead to plausible solutions.

[4] Major structures and sutures in SW Europe Variscides are well known (Figure 1), making it possible to infer the

boundaries of major (continental/oceanic) plates involved in the orogenesis. The main structure is dominated by the Iberian-Armorican Arc (IAA), easily reconstructed by inverting the opening of the Biscay Gulf. An overview of the IAA structure can thus be obtained across two radial transects. In Armorica, a steep slate belt (Central-Armorican Zone) separates a branch to the North with north verging structures (located along the English Channel) and a South Armorican Zone branch with south verging structures. In Iberia, a steep slate belt (Central-Iberian Zone–CIZ) separates a branch with E and NE verging structures, centripetal to the IAA, and a branch with W and SW verging structures, centrifugal to the IAA. Therefore the IAA continuity is easily recognized by the spatial correlation of structural style and bivergent symmetry (Figure 1).

[5] The next step is to locate the main Variscan sutures, using the standard paleogeodynamics criteria, such as faunal differentiations, ophiolite sequences, high-pressure metamorphic rocks, major thrusts and nappes, and paleomagnetic discontinuities. In the Armorican transect, a North Armorican suture along the English Channel and a South Armorican suture on both sides of the Central-Armorican Zone can be recognized. In the Iberian transect, the geodynamic meaning of the suture preserved within the Tomar-Badajoz-Córdoba sinistral shear (TBCSZ) zone is controversial. For some authors [*Matte*, 2001; *Simancas et al.*, 2001a] it represents a Variscan suture; for others [*Ribeiro et al.*, 1990; *Ribeiro*, 2000] it is a Cadomian suture reworked as an intraplate sinistral flower structure. The second interpretation is favored because there are no major paleogeographic differences in both sides of the suture during Paleozoic times [*Ribeiro et al.*, 1990]; these geological formations (suture rocks) are thus considered to be poly cyclical (i.e., Cadomian suture rocks, overprinted during the Variscan orogeny, as discussed below).

[6] In the Iberian Variscides, as well as in Armorica and Middle Europe, different lines of evidence support a polycyclic orogenic evolution. As observed in the Cantabrian, West-Asturian-Leonese (WALZ) and Ossa Morena (OMZ) Zones of the Iberian Terrane [*Ribeiro et al.*, 1990], the basal Cambrian rests on angular unconformity on Neoproterozoic sediments that were folded, cleaved and metamorphosed before Cambrian times [*Vera*, 2004; *Dias et al.*, 2006]. These Neoproterozoic metasediments must rest onto, or grade toward, a Gondwana cratonic basement (see section 3.1) as required by the stable sedimentary environment during deposition of the Lower Paleozoic in Iberia, Armorica and Middle Europe. The thick-skinned nature of Variscan tectonics within the internal zones of the Iberian Variscides (WALZ, CIZ and OMZ) induced the outcrop of this basement, even if strongly obliterated by the Variscan tectonothermal evolution, either in the Autochthon of OMZ and CIZ or the Continental Allochthonous Terrane of NW Iberia.

[7] In the OMZ, geochronological data [*Simancas et al.*, 2001b; *Salman*, 2004, and references therein] for several calc-alkaline plutons and associated metamorphic rocks provide similar hornblende and muscovite $^{40}Ar/^{39}Ar$ cooling ages of $\sim$575–550 Ma for different domains within the northern margin of the TBCSZ flower structure [*Dallmeyer and Quesada*, 1992]. Clearly, in those domains there was a Cadomian basement that should have been deformed/metamorphosed under (up to) the amphibolite facies before deposition of the Cambrian cover. In the axial zone of the flower structure, the older (Cadomian) ages were reset by Variscan tectonothermal events from $\sim$370–360 Ma to $\sim$340–330 Ma [*Dallmeyer and Quesada*, 1992]. However, recent geochronological data obtained through different methods [e.g., *Ordóñez Casado*, 1998] for suture rocks (including eclogites and oceanic amphibolites) inside the TBCSZ provided a scatter of dates, ranging from Lower Ordovician to Lower Carboniferous. The controversy on Cadomian versus Variscan cycles became more acute as a consequence of these conflicting or ambiguous dates. As a contribution to the ongoing debate a possible interpretation based on new field data is reported here, which should be further verified by new adequate geochronological data.

[8] As comprehensively described in sections 3.2 and 3.3, there is evidence for a Lower Ordovician continental rift migration from a position inside the TBCSZ (during Lower-Middle Cambrian times) toward the SW boundary of OMZ; this rifting process then evolved to the Rheic Ocean. Lower Ordovician continental rifting migration caused the "Sardic" unconformity in CIZ and OMZ [*Romão et al.*, 2005], representing a transient inversion that briefly interrupts the general Lower Paleozoic extensional regime in Iberia [*Vera*, 2004; *Dias et al.*, 2006]. This rift migration favored the establishment of a high geothermal regime at the Cambrian-Ordovician boundary, as recorded by widely distributed and extensive partial melting of Cadominan granitic basement and bimodal magmatism in OMZ and CIZ [*Simancas et al.*, 2001b; *Expósito*, 2000]. It is inferred that the Cambrian-Ordovician rifting was probably related to an ascending mantle plume and operated under a high heat flow mode; consequent thermal erosion must have thinned the preexisting Cadomian basement, causing the wide scatter of geochronological results obtained for both the high-pressure and oceanic suture rocks in TBCSZ. Subsequently, during the Variscan orogeny, the TBCSZ rocks were recrystallized and strongly deformed under low-pressure amphibolite facies conditions. A similar evolution is recorded in the Continental Allochthonous Terranes of NW Iberia; however, the presence of far-traveled thrust nappes in these thrust complexes adds further difficulties to distinguish Cadomian and Variscan events as discussed below.

[9] The only rooted Variscan suture in Iberia is the SW Iberia boundary between the Ossa-Morena Zone (OMZ, which is considered the SW margin of the Iberian Plate), and the South Portuguese Terrane Plate. Nevertheless, in NW Iberia, allochthonous Variscan suture rocks occur within a vertical succession of thrust sheets including (Figure 2), from top to bottom, a Continental Allochthonous Terrane (CAT), an Ophiolitic Complex and a continental rifting, bimodal magmatic Basal Complex that underwent high-pressure metamorphism [*Ribeiro*, 1976, 1987, 1988; *Munhá et al.*, 1984]. Structural criteria indicate that major thrust transport changes from sheet to sheet, but always with

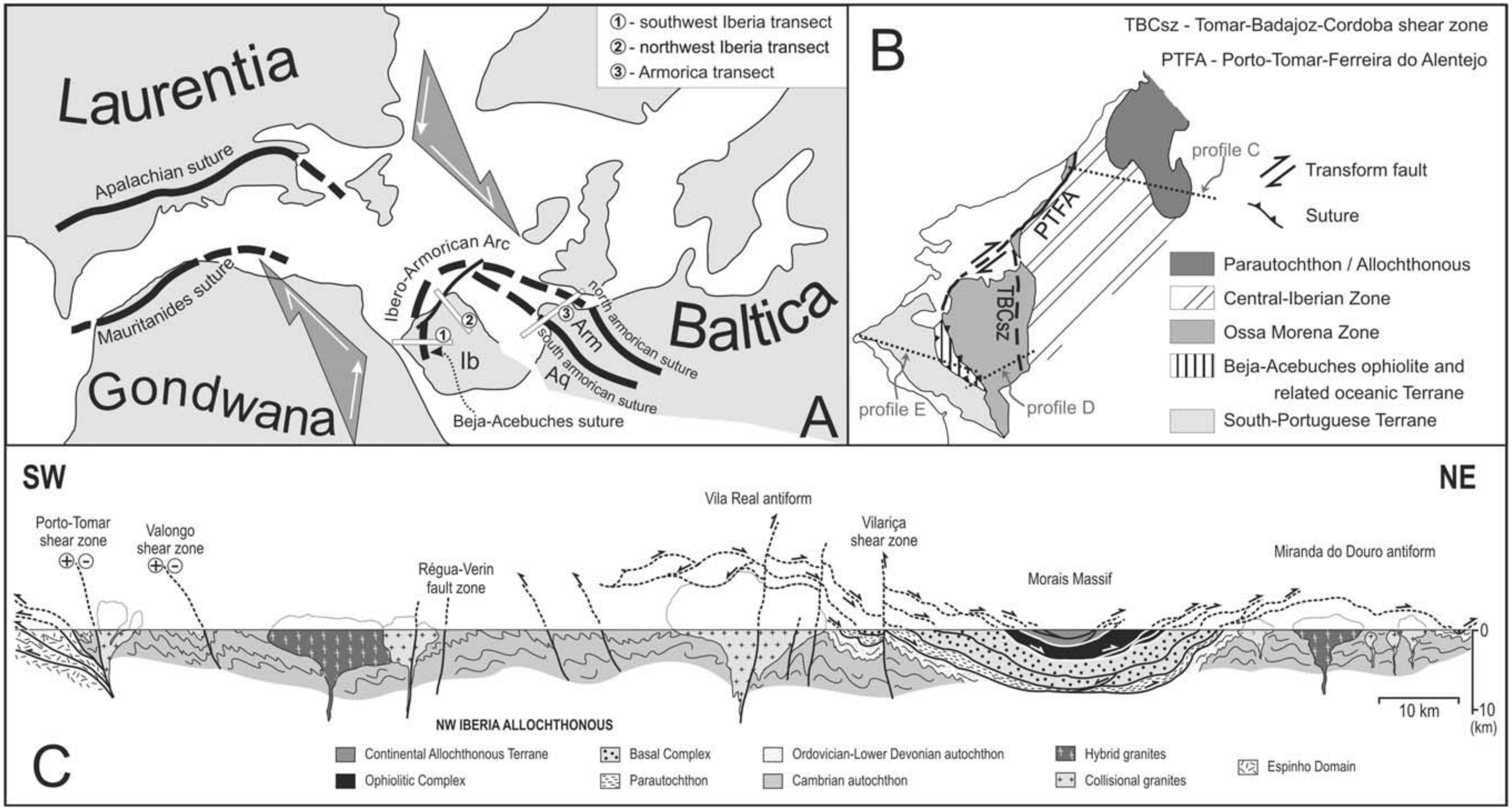

Figure 1. (a) Periatlantic Variscan orogens produced by dextral transpression: location of sutures and selected transects. (b) Terranes, sutures, transforms, allochthonous complexes, and tectonic zones inside the Iberian Terrane of W Iberia. (c) Geological profile on the autochthon and allochthonous complexes of NW Iberia across of Douro Valley [after *Rodrigues et al.*, 2006; *Ribeiro et al.*, 2006]. Location is shown in Figure 1b. (d, e) Geological profile on the OMZ and SPT of SW Portugal. Location is shown in Figure 1b.

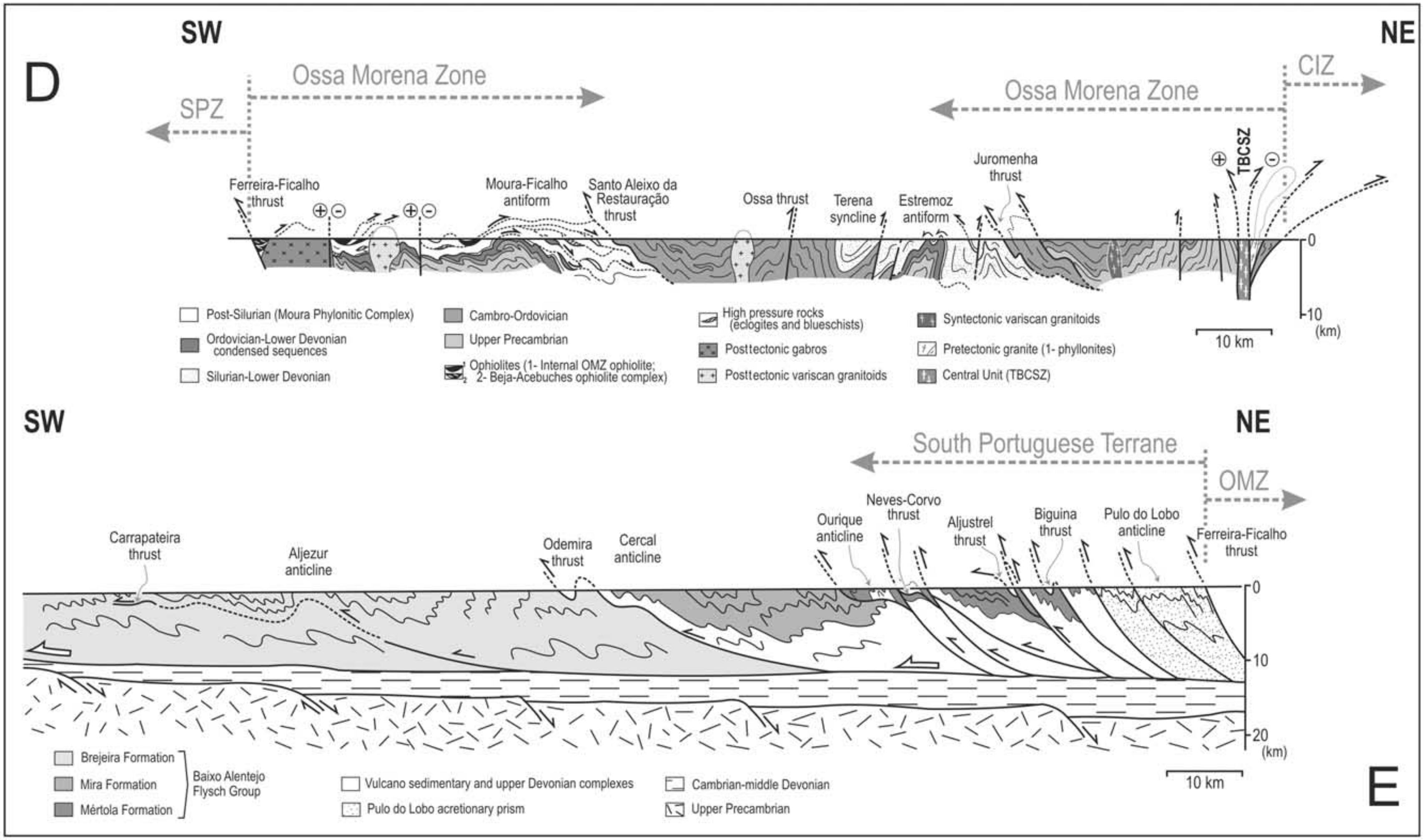

Figure 1. (continued)

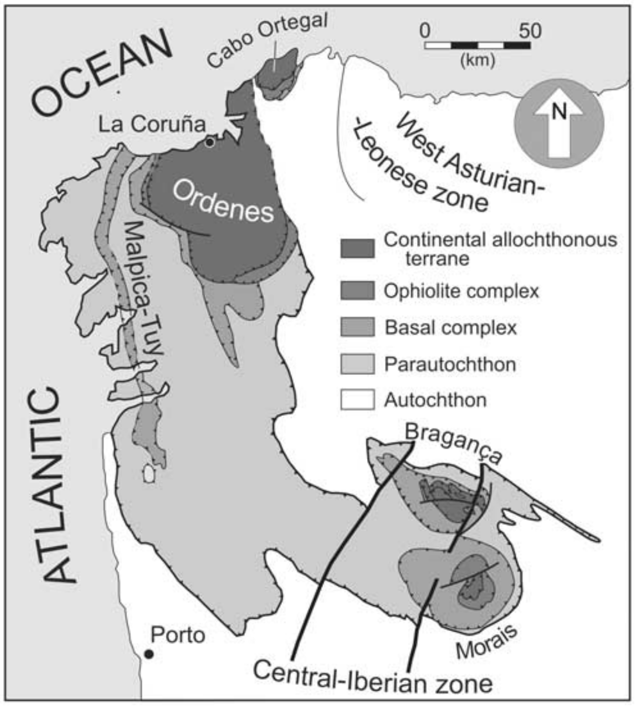

Figure 2. NW Iberia Allochthonous Complexes and terranes emplaced on top of the Centra-Iberian and West-Asturian-Leonese autochthon.

a centripetal component relative to the Ibero-Armorican Arc [*Ribeiro et al.*, 2003]. This fact suggests that the root zone of the CAT must be in the South Armorican Suture where a similar succession of nappes has been described, while the Ophiolitic and the Basal Complexes are rooted in the domain at the intersection of Paleotethys and the Porto-Tomar-Ferreira do Alentejo shear zone (PTFASZ) described below [*Ribeiro et al.*, 2003].

[10] The vertical succession and the spatial distribution of the NW Iberia Allochthonous [*Iglésias et al.*, 1983; *Marques et al.*, 1992, 1996] indicate that the upper thrust sheets have larger displacements than the lower ones. Thus, from bottom to top, the stretched margin of Iberia (represented by the Basal Complex) gradually evolves to an ocean, whose remnants are preserved in the Ophiolitic Complex, which will be called here Paleotethys. The continent to the west and north side of this ocean is preserved in the CAT. This upper allochthonous complex, overlaying the ophiolite, is represented by two major thrust sheets: an Upper CAT with low- to medium-grade metamorphic rocks, well preserved in the Ordenes and Morais Massifs; and a Lower CAT with very high grade metamorphic rocks (mostly mafic and minor felsic granulites, gneisses and eclogites) variably retrogressed during Variscan orogeny, particularly well exposed in the Cabo Ortegal and Bragança Massifs. Similar rocks occur within minor duplexes below the Upper CAT, either in the Ordenes (the so-called Mellid Unit [*Martínez Catalán et al.*, 2002]) or in the Morais Massifs (the Vinhas-Caminho Velho Units [*Marques et al.*, 1992]. Accordingly, major compositional and rheological features of evolved continental lithosphere are preserved in CAT; the Upper CAT corresponding to upper/middle crustal levels and the Lower CAT representing lower crust (and upper subcontinental mantle?).

[11] The NW-Iberia W-E transect is located at the IAA hinge (Figure 1), between the N-S Armorica transect and the NW-SE SW-Iberian transect; it represents an important link to correlate Armorican and SW-Iberian transects. This interpretation is based on two detailed geological profiles: one is located near the northern Spanish coast [*Pérez-Estaún et al.*, 1991; *Ribeiro and Sanderson*, 1996] and is complemented by deep seismic reflection data; the other is a new, updated profile near the Lower Douro valley, in Northern Portugal [*Ribeiro et al.*, 2006; *Rodrigues et al.*, 2006], crossing the NW Iberia Allochthonous and the CIZ Autochthon reaching the contact with the PTFASZ (see Figure 1c). However, the link to correlate Armorican and SW-Iberian is incomplete because the root zone of NW Iberia Allochthonous is in an offshore position. Moreover, the NW-Iberia W-E transect is displaced by the Porto-Tomar-Ferreira do Alentejo transform and modified by Mesozoic lithospheric thinning caused by the Atlantic opening. Notwithstanding these difficulties, geology of the NW-Iberia W-E transect is well known onshore [*Ribeiro et al*., 1990; *Pérez-Estaún et al.*, 1991] and has been imaged by deep reflection seismic profiles. Thus the available information on the NW-Iberia W-E transect should be significant to any synthesis of the Ibero-Armorican geodynamic evolution.

[12] The SW Iberian transect (Figure 1a) consists of two detailed geological profiles; the Spanish segment is complemented by the IBERSEIS [*Simancas et al.*, 2003]. The updated version of the Portuguese segment (Figure 1d) is located in "en echelon" relative to the Spanish segment, consistent with the transpressive regime of SW Iberia [*Ribeiro and Sanderson*, 1996].

[13] In contrast with observations in the SW Iberian transect, in the Armorican transect two rooted sutures were recognized. Furthermore, the once continuous Central-Iberian and Central-Armorican Zones (as suggested by stratigraphic relations [*Robardet and Gutiérrez-Marco*, 1990; *Robardet*, 2003]) are now located, respectively, in the inner Arc segment at Iberia and in the outer arc segment at Armorica; that is, they are on opposite sides of the South-Armorican Suture. A possible explanation for this paradox was proposed by *Munhá et al.* [1984] and will be discussed below.

[14] The geological criteria referred to above must be integrated with paleomagnetic data in order to locate plates and oceans involved in orogenesis. According to the available data, it is possible to conclude that a major ocean, the Rheic, separates Avalonia from Armorica and Iberia. Additionally, the Paleotethys minor ocean [*Stampfli and Borel*, 2002] (also called Massif Central-Galicia Ocean by *Matte* [2002]) separates Armorica from Iberia. Paleotethys must have been a narrow ocean because there is neither a record of a large paleomagnetic difference nor a significant stratigraphical differentiation between Iberia and Armorica

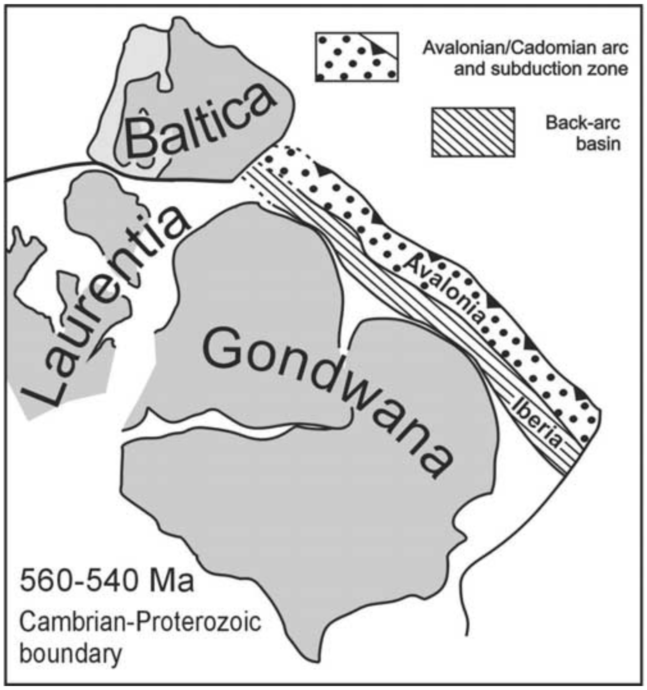

Figure 3. Paleogeographic reconstruction at the end of Cadomian orogeny (560–540 Ma), displaying the location of Iberia and Avalonia relative to Gondwana, Laurentia and Baltica, as well as the inferred trace of Avalonian/Cadomian arc, subduction zone and back-arc basin.

[*Robardet*, 2003]. Another view on the paleogeography of Paleotethys is that it could represent a more or less continuous group of small ocean basins that extended further toward SW, between Iberia and Gondwana. In this scenario, the Paleotethys small ocean basins were separated from the wide Rheic Ocean by microcontinents (now represented by gneisses and eclogites) previously detached from Gondwana and now preserved as klippen of Finisterra (micro-) plate on top of OMZ (see below).

[15] The evolution of these oceans and plates during the Paleozoic should now be traced on the light of the Wilson Cycle concept; the possible causal interplaying between these major geotectonic units must also be established. In this context, it is important to emphasize that onshore field relationships and offshore geophysical data strongly suggest that the dextral PTFA shear zone connects the SW Iberia and the South Armorica sutures. Therefore the development of this shear zone played a major role during all the geodynamic evolution of SW Europe Variscides, explaining the presence of two oceans in Armorica and only one in Iberia.

3. Major Trends in Geodynamic Evolution

[16] In the following sections, the most crucial events characterizing the geodynamic evolution of SW Variscides will be discussed. The discussion is integrated within its specific time framework, reflecting the major perturbations on the general (steadier state) evolutionary orogenic path.

3.1. Cambrian-Proterozoic Boundary (~560–540 Ma)

[17] The available reconstructions show a major discontinuity at the end of the Cadomian orogenic cycle, preserving relicts of previous tectonic cycles. Avalonia, Armorica and Iberia are located (Figure 3) on the upper plate of the active Cadominan northern convergent plate boundary of Gondwana [e.g., *Fernández-Suaréz et al.*, 2000].

[18] The Cadomian basement of Iberia is mainly composed of magmatic rocks generated in an arc setting further subjected to back-arc extension filled with Neoproterozoic sediments [*Fernández-Suaréz et al.*, 2000]. Relicts of previous orogenic belts include the Early Proterozoic (1.9 Ga) low-pressure granulites that outcrop in the Atlantic margin of the Cantabrian Zone [*Guerrot et al.*, 1989], suggesting that this basement was part of the Gondwana Continent. The high-grade Cadomian Gondwana basement was only slightly affected by subsequent tectono-metamorphic events and acted as a rigid indentor during the Variscan cycle; this is in contrast with the Paleozoic evolution of the surrounding low-grade Cadomian sequences. Possible Grenville inliers are represented by occurrences of garnet-sillimanite quartzites (preserving high-temperature fabrics) in the Finisterra microplate [*Fernández et al.*, 2003] and kyanite-rich quartzites in lower grade Neoproterozoic metasedimentary sequence of the OMZ [*Orozco and Pascual*, 1975]; these occurrences may have the same genesis that as similar rocks of Paleoproterozoic age of the Canadian shield [*Church*, 1967; *Chandler et al.*, 1969].

[19] Polymetamorphic rocks included in the Lower CAT of NW Iberia as well as in the core of the TBCSZ are still controversial concerning their age and geodynamic significance. Our preferred interpretation envisages them as part of Cadomian basement overprinted by subsequent Variscan thermometamorphic events; however, other authors ascribe their formation to a polyphasic, but monocyclic Variscan evolution. These features will be addressed below within the time frame of the Variscan orogenic evolution.

3.2. Ordovician-Cambrian Boundary (~500–470 Ma)

[20] Continental rifting on the Cambrian platform of northern Gondwana started around the Middle Cambrian times (Figure 4) and subsequent opening of Rheic Ocean took place near the Ordovician-Cambrian boundary, at ~500–470 Ma. Bimodal extensional magmatism is recorded in the Autochthon of Iberia and Armorica, being contemporaneous with a break up unconformity and a transient inversion, known as the Sardic phase [*Romão and Ribeiro*, 1993; *Romão et al.*, 2005]. This event is also recorded in the Upper CAT units of NW Iberia and South Armorica. Gabbroic intrusions, that underwent intermediate to low-pressure granulite facies metamorphism (such as those of Monte Castelo in Ordenes [*Andonaegni et al.*, 2002]), were recently dated of 499 ± 2 Ma [*Abati et al.*, 1999]. In the Morais Massif, similar mafic dykes cut the Lagoa orthogneiss (sheared Cadomian granite [*Marques et*

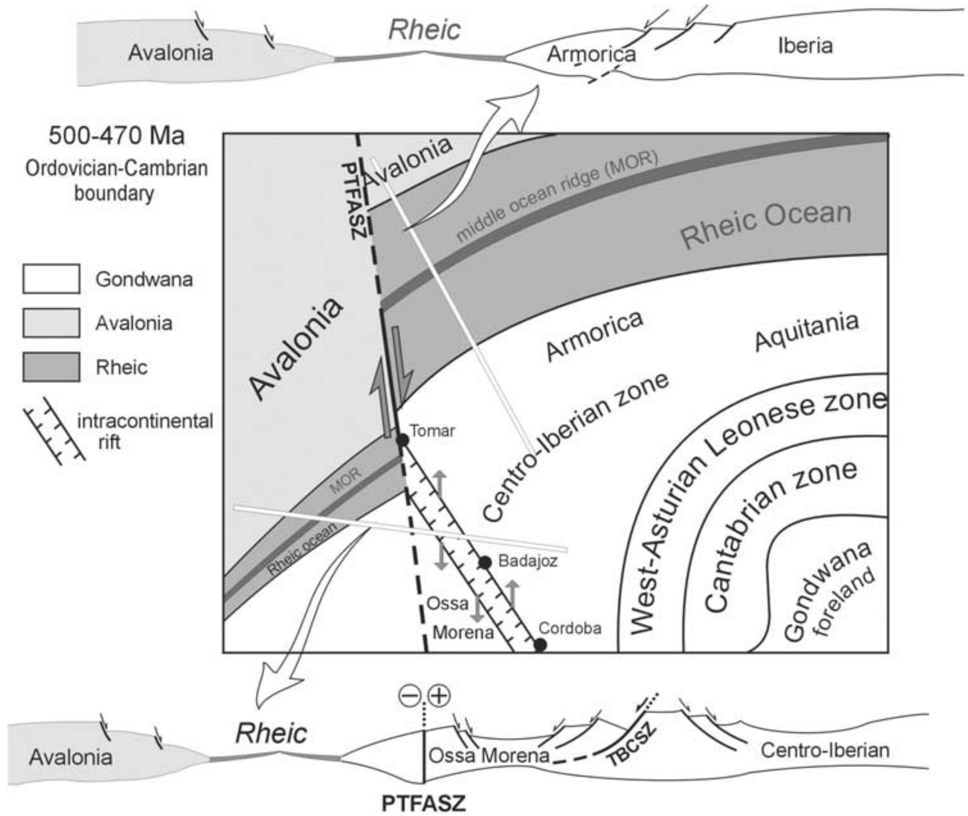

Figure 4. Paleogeographic reconstruction at 500–470 Ma of Armorica-Iberia, Avalonia, Gondwana, and Rheic Ocean; PTFASZ (transform zone) and TBCSZ (oblique slip intracontinental rift); and NW Iberia-Armorica and SW Iberia traverses.

al., 1992]), requiring high-level brittle failure to allow dyke intrusion under low P-T metamorphic conditions; high heat flow related to magma intrusion caused the resetting of Cadomian ages of the Lagoa orthogneiss at 496 + 3/ −2 Ma [*Dallmeyer and Tucker*, 1993; *Ribeiro et al.*, 1993]. Similar intrusions can also be found in the Lower CAT units of Cabo Ortegal and Bragança Complexes, as well as in the small duplexes of Sobrado-Mellid (below Ordenes) and Vinhas-Caminho Velho (below Morais). In these Lower CAT units, the main rock types are high-pressure mafic granulites, gneisses and eclogites with metamorphic ages of 485–495 Ma [*Fernández-Suaréz et al.*, 2002], being intruded by layered mafic-ultramafic bodies (similar to those found in the higher level thrust complexes) at ~500 Ma. The original relationship between high-pressure/high-temperature (granulites) and mafic-ultramafic intrusives can be established in the Bragança Complex [*Marques et al.*, 1996], where low/intermediate pressure meta-gabbroic and associated ultramafic granulites cut previously deformed and metamorphosed high-pressure rocks; indeed, the P-T-t path for the intrusive meta-gabbros and the high-pressure rocks is clearly distinct [*Marques*, 1993]. The high-pressure rocks (15–30 kb) underwent a complex clockwise path indicative of subduction/collision and exhumation, whereas later meta-gabbros show only isobaric cooling at 8 kb from 1000°C to 700°C. Afterward, both the high-pressure rocks and meta-gabbro/ultramafic intrusives follow the same exhumation and retrogression path during the Variscan Orogeny, starting at ~390 Ma. This suggests that the heat anomaly persisted at depth for about 100 Ma, controlling Cadomian basement geochronological resetting at ~500 Ma and the décollement near the crust-mantle boundary that induced the basal thrust of CAT. New geochronological data [*Santos et al.*, 2005] and thermochronological modeling [*Munhá et al.*, 2005a] support this interpretation, suggesting that polymetamorphic rocks of Bragança Massif CAT were affected by high-pressure metamorphism older than 460–500 Ma, followed by long-term heating sustained by magma underplating related to rifting during Lower Paleozoic times.

[21] The thinning of Cadomian basement is also reflected in the present-day distribution of thrust units, once included in a continuous continental Terrane [*Marques et al.*, 1996]. A major extensional shear zone detached this Terrane, preserving lower crustal levels on its eastern domains (current geographical coordinates; Cabo Ortegal and Bragança Massifs) and upper crust on its western domains (Ordenes and Morais Massifs) that underlie duplexes of lower crustal units. This major detachment requires an oceanic realm to the west of the CAT root zone, which is interpreted as the Rheic ocean basin. Accordingly, the CAT of NW Iberia should be toward the eastern side of Rheic,

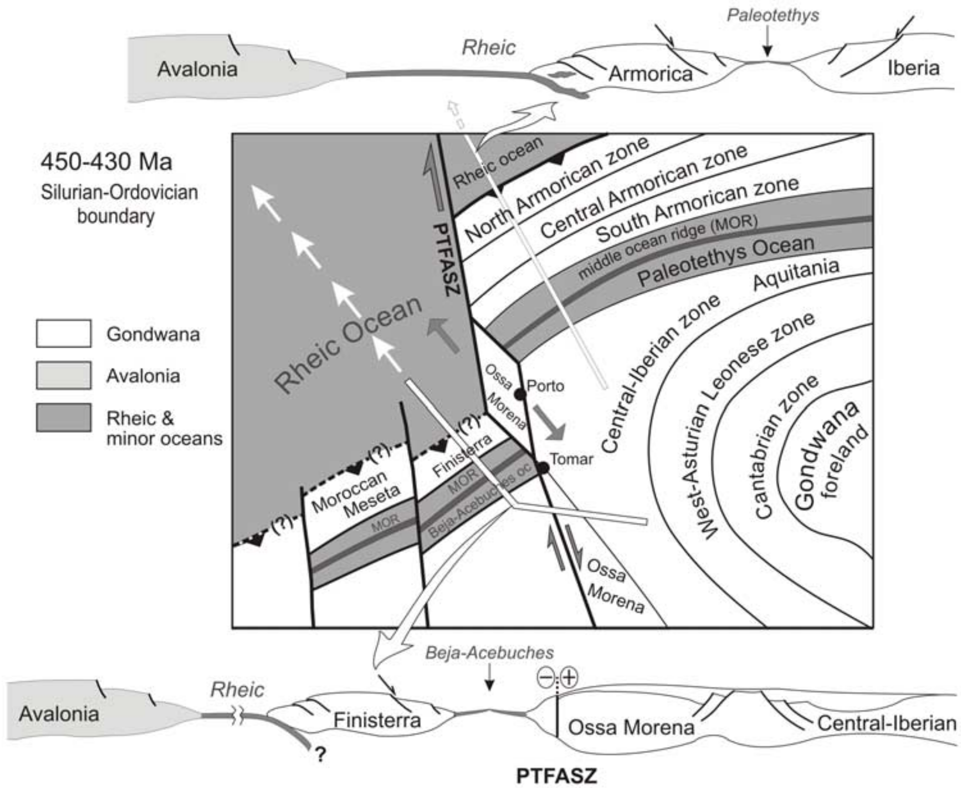

Figure 5. Paleogeographic reconstruction at 450–430 Ma of Armorica, Iberia, Gondwana, Finisterra, Moroccan Meseta, Rheic and Paleotethys oceans (PTFASZ (transform zone)), and NW Iberia-Armorica and SW Iberia traverses.

being part of the Armorican Plate assemblage (and not Avalonian) [*Martínez Catalán et al.*, 1997].

[22] As referred above, along the TBCSZ (on the southwestern branch of the Variscan chain, OMZ), Cadomian rocks of variable metamorphic grade (including eclogites and ophiolitic fragments), are also cut by Lower Paleozoic intrusions (530–470 Ma) coeval with bimodal transitional/alkaline basaltic to (per-) alkaline rhyolitic/trachytic sequences that record an aborted rifting event [*Mata and Munhá*, 1990; *Galindo and Casquet*, 2004; *Solá et al.*, 2005, 2006]. At this stage, there is no major discontinuity within the Paleozoic sedimentary record [*Dallmeyer and Ibarguchi*, 1990], implying that during Cambrian–early Ordovician times the OMZ should be envisaged as a passive margin, probably with a major fossil transform component relative to the Iberian plate.

[23] According to the existing paleomagnetic reconstructions [*McKerrow et al.*, 2000; *Tait et al.*, 2000], Avalonia drifted from Gondwana, as a consequence of the Rheic Ocean opening. Armorica and Iberia were still attached to the Gondwana major plate.

3.3. Ordovician-Silurian Boundary (~450–430 Ma)

[24] During the Ordovician, Rheic becomes a wide ocean and a passive margin type evolution proceeds both in Armorica and Iberia [*Crowley et al.*, 2000]. A siliciclastic platform is established in both Armorica and the Iberian terrane (*Azor* [2004] cited by *Vera* [2004]), leading to development of the widespread (Arenig) Armorican Quartzite Formation that should have been deposited near a stable Gondwana cratonic area. The Armorican Quartzite depositional features suggest a noncatastrophic and highly diachronic process (ranging from the Upper Cambrian to Lower Ordovician (?)) that was continuous from a deeper sedimentation in the OMZ toward a shallow marginal facies in the CIZ. This indicates paleogeographic continuity between the OMZ and other zones of Iberia during Lower and Middle Ordovician times. At the end of the Ordovician (Figure 5) a new rifting episode starts, opening the Paleotethys Ocean [*Stampfli and Borel*, 2002]. Tholeitic magmatism during Caradoc times was followed by felsic magmatism in the autochthon of Armorica and Iberia, lasting until the end of Silurian. The Basal Complex of NW Iberia allochthonous also records rifting and coeval bimodal magmatic activity, including widespread peralkaline volcanics [*Ribeiro*, 1987], strongly suggesting that rifting was assisted by mantle plume activity [*Crowley et al.*, 2000].

[25] The opening of Paleotethys causes drifting of Armorica from Iberia and Aquitania (formerly continuous and now separated by the Mesozoic opening of the Bay of Biscay) toward the south of the southern Armorican suture. Stratigraphic and paleogeographic data [*Robardet*, 2002,

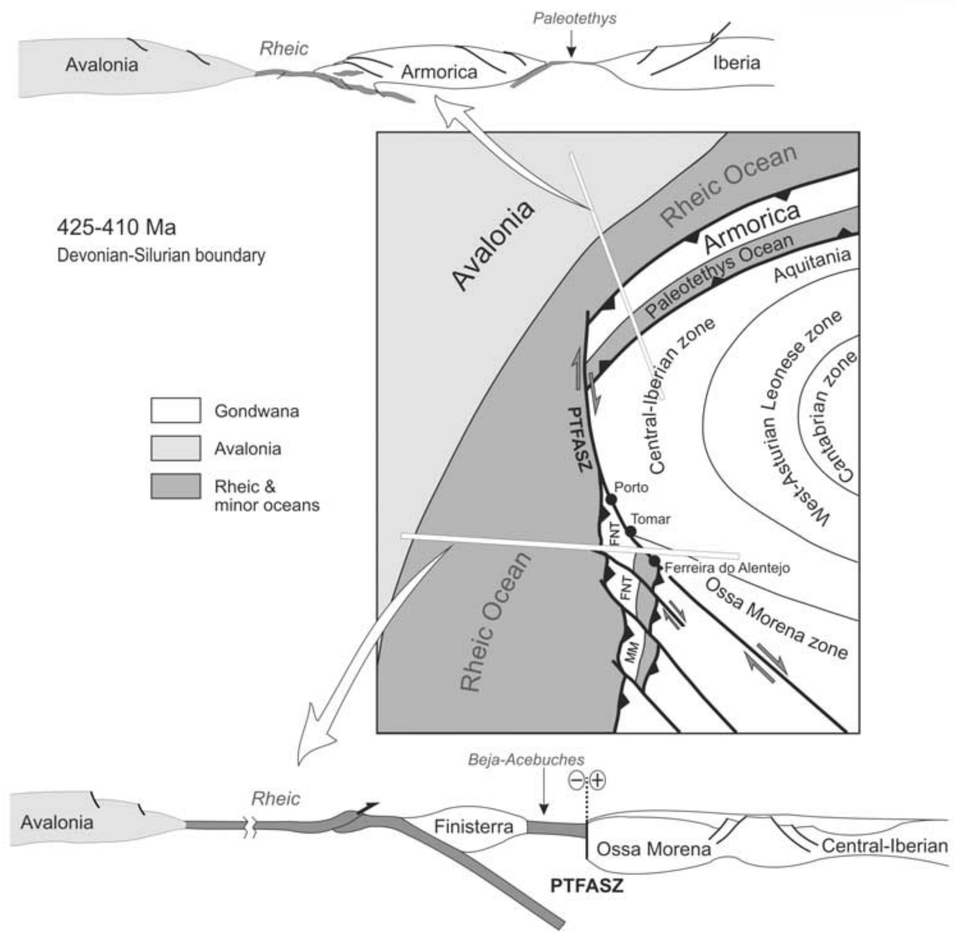

Figure 6. Paleogeographic reconstruction at 425–410 Ma of Avalonia, Armorica, Iberia, Gondwana, Finisterra Moroccan Meseta, Rheic, and Paleotethys and Beja-Acebuches oceans; PTFASZ (transform zone) and TBCSZ (oblique slip intracontinental rift); and NW Iberia-Armorica-Avalonia and SW Iberia-Avalonia traverses.

2003] exclude a major ocean basin because there is no faunal differentiation from Ordovician to Lower Devonian. Moreover, available paleomagnetic data do not show significant paleo-latitude differences between Armorica and Iberia at that time [*Matte*, 1991, 2001]. Relationships between the evolution of Paleotethys and Rheic Oceans will be discussed below.

3.4. Silurian-Devonian boundary (∼425–410 Ma)

[26] At these times, closure of the Rheic Ocean had already started (Figure 6) but continental collision with Avalonia had not yet occurred. Slow closure of Paleotethys has begun, and this oceanic realm expanded toward SW. Meanwhile, the Iberian-Aquitania plate was subducted below Armorica with simultaneous synthetic obduction of Paleotethys lithosphere. Toward the SW of Armorica, the PTFA shear zone connected the (closure) boundary of Paleotethys and its extension to SW in a small ocean where BAOC was generated. Two additional (micro-) plates play an important role at this evolving stage: the Finisterra continental plate (see below), dragged to the North by dextral movement along PTFA shear zone and an oceanic plate represented by the so-called Internal Ossa-Morena Zone Ophiolitic Sequences (IOMZOS), which reflect antithetic obduction, coupled with flake tectonics, during subduction of Rheic oceanic lithosphere. After being stacked on top of Finisterra plate margin, which was partially underthrusted to reach eclogite and blueschist facies conditions, these sequences were finally transported on top of OMZ by the overtaking of BAOC sequences [*Fonseca and Ribeiro*, 1993; *Fonseca et al.*, 1999]. The upper levels of the Finisterra Plate were obducted on top of Iberia, whereas its lower units were completely subducted below Iberia. This process was initiated by intraoceanic thrusting, antithetic to subduction of Rheic below Finisterra and Iberia or, further South, below Gondwana. Subsequent evolution is shown in the next sections (see sections 3.5, 3.6, and 3.7 and Figures 7, 8, and 9).

[27] Consumption of the wide Rheic Ocean and minor Paleotethys (including its SW extension) caused an increase of IAA curvature by transform movement along the dextral

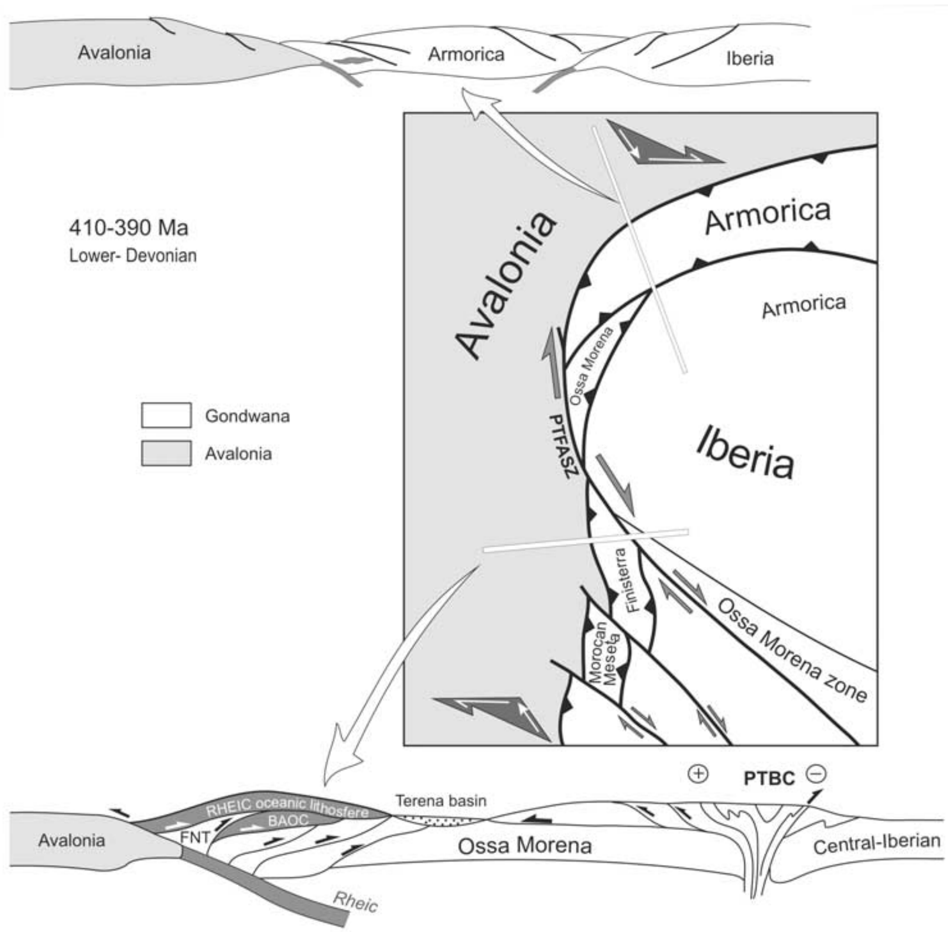

Figure 7. Paleogeographic reconstruction at 410–390 Ma of Avalonia, Armorica, Iberia, Gondwana, Finisterra and Moroccan Meseta, displaying Rheic, Paleotethys, BAOC and IOMZOS oceanic domains; PTFASZ transform zone, TBCSZ oblique slip intracontinental rift, and Terena basin in the Ossa Morena Zone; and NW Iberia-Armorica-Avalonia and SW Iberia-Avalonia traverses.

PTFA shear zone. Though this curvature increased (Figure 7), the paleogeographic zones, initially straighter and slightly oblique to each other, become nearly parallel, roughly delineating the location and geometry of subsequent active tectonic zones. In particular, the paleogeographic boundary between OMZ and CIZ becomes subparallel to the Variscan tectonic trend around the IAA.

3.5. Lower/Middle Devonian Boundary (∼390–370 Ma)

[28] After a transitional Lower Devonian stage (∼410–390 Ma) (Figure 7), a major event occurred at ∼390–370 Ma, corresponding to the final closure of both Rheic and Paleotethys (Figure 8). In NW Iberia, Carreon (Ordenes) and Morais ophiolites, representing the Paleotethys ocean floor, reveal protolith ages of ∼400 Ma [*Pin et al.*, 2000, 2005] soon followed by regional intermediate-pressure metamorphism dated at 390–370 Ma [*Dallmeyer et al.*, 1991; *Munhá et al.*, 2005b]. These data and the presence of an inverted metamorphic sole below the ophiolite [*Ferreira*, 1965; *Ribeiro*, 1974] suggest hot obduction on top of the NW Iberian Allochthonous Basal Complex; ophiolite obduction was immediately followed by CAT overthrusting (Figure 9), inducing amphibolite/granulite facies recrystallization of the obducted ophiolite complex. Thickening/burial of the NW Iberian Allochthonous Basal Complex wedge to the West and below the ophiolite thrusts induced metamorphic recrystallization ranging from blueschist facies in the East to the eclogite facies toward the West [*Ribeiro*, 1976, 1988; *Munhá et al.*, 1984; *Ibarguchi et al.*, 1989].

[29] In South Armorica, the thrust wedge is displaced by later dextral shears but shows a similar zonation with blueschists in the South (350 ± 10 Ma in Groix [*Bosse et al.*, 2000]) and eclogites to the North [*Martelet et al.*, 2004]. The usual interpretation is to invoke subduction centrifugal to IAA both in Armorica and Iberia, carrying the usual conceptual complexities related to exhumation of high-pressure from very deep levels (∼60 km) to the present erosion surface; plausible explanations are possible and will be discussed below.

[30] Paleotethys closure induces the collision between Armorica (to the N and W) and Iberia (to the S and E),

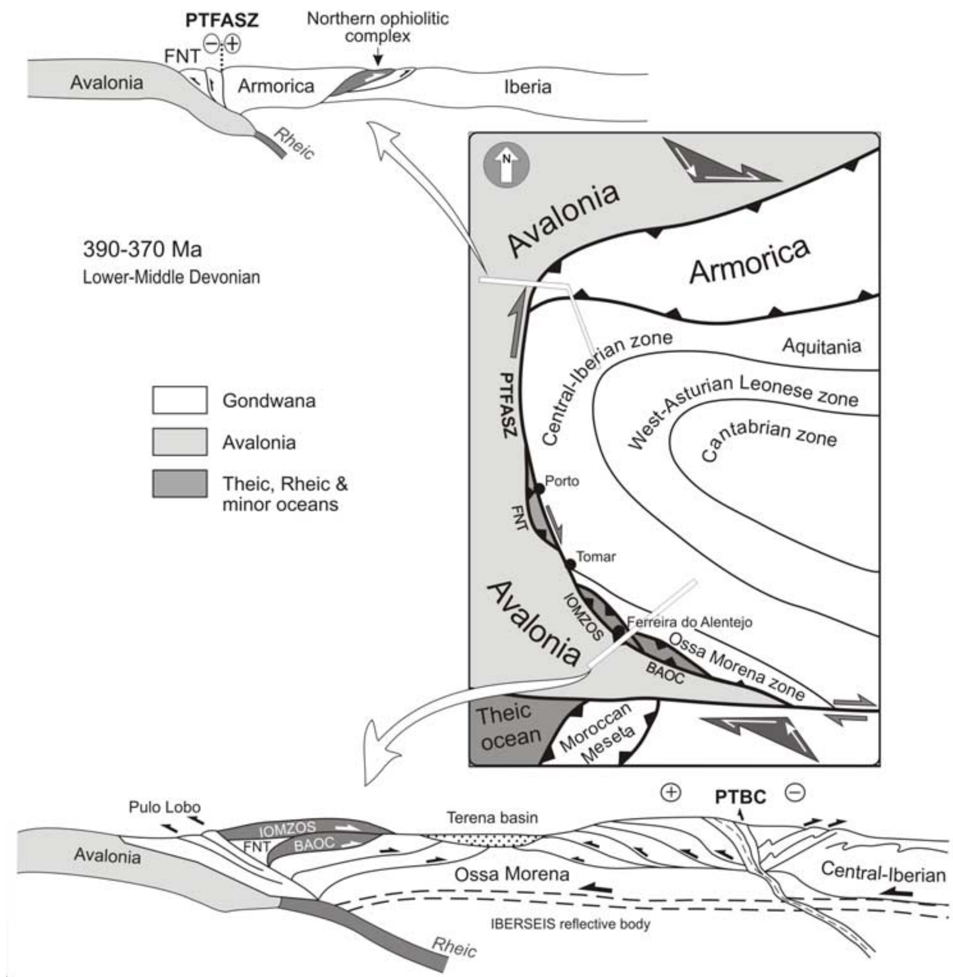

Figure 8. Paleogeographic reconstruction at 390–370 Ma of Avalonia, Armorica, Iberia, Gondwana, Finisterra, and Moroccan Meseta. Rheic, Theic, and other minor oceanic domains are also shown, as well as PTFASZ transform zone, TBCSZ oblique slip intracontinental rift, and Terena basin in the Ossa Morena Zone, and NW Iberia-Armorica-Avalonia and SW Iberia-Avalonia traverses.

along the IAA. The Iberia-Aquitaine plate is underthrust below Armorica as deduced from surface tectonics and deep seismic profiling [*Martelet et al.*, 2004].

[31] The available geochemical data for the NW Iberia ophiolites [*Pin et al.*, 2000, 2005] strongly suggest a back-arc basin tectonic setting for Paleotethys; thus, opening of this minor ocean could has been induced by (the major) Rheic Ocean subduction [*Stampfli and Borel*, 2002] under Armorica and Iberia. In both Armorica [*Crowley et al.*, 2000] and SW Iberia there is no evidence of convergence before the end of Silurian, but this convergence is marked by the oldest Lower Devonian syntectonic flysch sequences.

[32] New geochronological results [*Munhá et al.*, 2005b] date metamorphic peak conditions on the NW Ophiolitic Complex in the Morais Massif at 375 Ma with subsequent rapid cooling during exhumation; geothermobarometric data [*Munhá and Mateus*, 2005] suggests that the top of this complex was buried and initially heated up because downward heat conduction from the overlying CAT high-grade rocks. Coupled with ophiolite protolith ages of ~400 Ma [*Pin et al.*, 2000], these data give further support to the hypothesis that Paleotethys was never a large fast spreading ocean.

[33] In SW Iberia a major suture between OMZ (as part of the Iberian Plate) and South Portuguese Terrane (SPZ) is recognized by detailed geological mapping and supported by petrofabric analysis, mineralogical and petrological/geochemical data [*Munhá et al.*, 1986; *Quesada et al.*, 1994; *Fonseca and Ribeiro*, 1993; *Fonseca et al.*, 1999; *Mateus et al.*, 1999; *Figueiras et al.*, 2002]. This major suture is also consistent with geophysical data obtained both from deep seismic reflection profiling [*Simancas et al.*, 2003] and magnetotelluric profiles [*Santos et al.*, 1999, 2002; *Almeida et al.*, 2001, 2005; *Pous et al.*, 2004]. Obduction is recorded both by the (back-arc basin [*Quesada et al.*, 1994]) Beja-Acebuches Ophiolite Complex (BAOC) and the IOMZOS far-traveled klippen [*Fonseca et al.*, 1999; *Pedro et al.*, 2005] rooted in the suture of a major ocean up to 50 km to

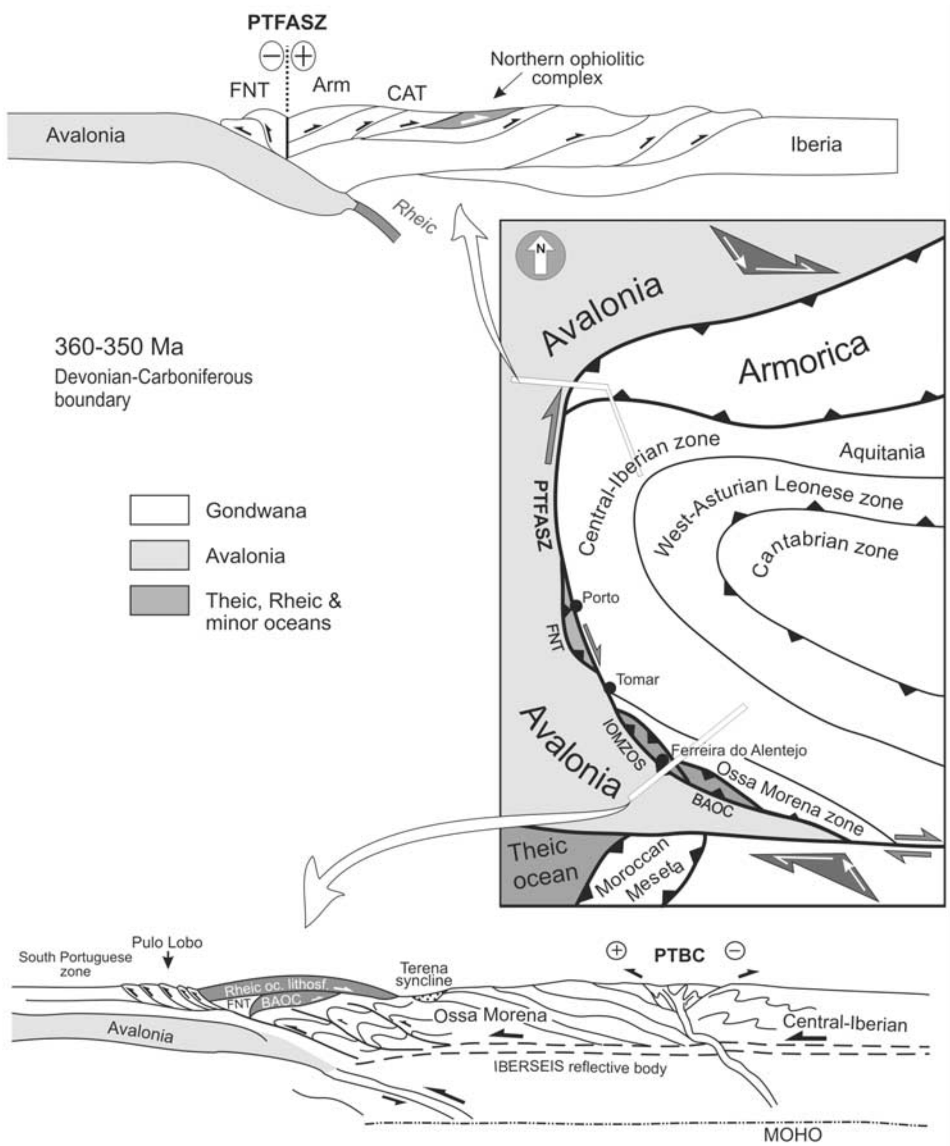

Figure 9. Paleogeographic reconstruction at 360–350 Ma of Avalonia, Armorica, Iberia, Gondwana, Finisterra, Moroccan Meseta; Rheic, Theic, and minor oceans; PTFASZ transform zone, TBCSZ oblique slip intracontinental rift, and Terena basin in Ossa Morena Zone; and NW Iberia-Armorica-Avalonia, SW Iberia-Avalonia, Pulo do Lobo occidental domain (accretionary prism), and South Portuguese terrane traverses.

the NE. These events occurred in the time ranging between the deposition of the Lower Devonian Terena flysch [*Pereira et al.*, 1999] and the unconformable Middle Devonian sequences in OMZ.

[34] The Moura Phylonnitic Complex [*Araújo et al.*, 2005] is an accretionary sequence of ophiolitic slices, mafic alkaline and peralkaline metavolcanics, as well as metasediments that were derived from the relative autochthon of the Finisterra Terrane or OMZ of the Iberian Plate. It is considered that this complex was rooted in the SW suture between OMZ of the Iberian Terrane and South Portuguese Terrane. Indeed, the earliest tectonic events in the Moura Phylonnitic Complex display thrusting with top to NE (present geographical coordinates), including ophiolite and eclogite nappes on top of volcano-sedimentary slices that recrystallized under blueschist facies conditions [*Araújo et al.*, 2005]. High-pressure metamorphism was dated at ~370 Ma [*Moita et al.*, 2005c] and field relationships clearly exclude the provenance of these high-pressure rocks from the same root zone that feed the suture rocks along in the TBCSZ axis. Owing to opposite senses of thrusting, the tip of the Iberian lithospheric indentor became highly unstable, allowing material being incipiently subducted (and, afterward, eventually obducted) to the present position inside the accretionary complex.

[35] Eclogites developed a clockwise P-T path that reached 16–18 kbar and 600°–650°C, followed by near isothermal decompression to 12–10 kbar before final cooling (<550°C) to greenschist facies conditions [*Fonseca et al.*, 1999]. Rapid exhumation (∼370–360) [*Moita et al.*, 2005c] was induced by channel flow and/or flake mechanisms, operating at undefined variable depths, depending on the real effects of tectonic overpressure. This mechanism, operating in a flake–double wedge context, is supported by deep seismic reflection profile [*Simancas et al.*, 2003; *Rosas*, 2003] and by contemporaneous mafic calc-alkaline orogenic magmatism (e.g., Veiros-Vale Maceira and Campo Maior at ∼360–370 Ma [*Carrilho Lopes et al.*, 2006; *Moita et al.*, 2005b]) as well as ophiolite obduction in OMZ. Therefore the geodynamic evolution of SW Iberia high-pressure events is coeval with that of equivalent rocks in Armorica and NW Iberia, suggesting simultaneous closure of Paleotethys and Rheic in SW Iberia.

[36] The PTFA dextral shear zone plays a major role on relating SW Iberian and NW Iberian sutures. This shear zone was active during the whole Variscan cycle, affecting the TBCSZ megashear, which represented an aborted continental rift during Lower Paleozoic times and evolved to a sinistral Variscan flower structure in the upper Paleozoic [*Ribeiro et al.*, 1990]. The sinistral component of displacement to WNW of TBCSZ decreases as it approaches the PTFA dextral shear zone, which was not deformed by the TBCSZ. Accordingly, it is proposed that the PTFA shear zone represents a transform type boundary, whereas TBCSZ would act as a conjugate intraplate shear zone with NNE-SSW shortening (compatible with the dextral displacement in N-S segment of the PTFA shear zone). These observations, taken together with the aforementioned arguments on the uncertainties on age dating of OMZ-CIZ suture rocks, as well as the lack of Lower Paleozoic paleogeographic discontinuity among OMZ/CIZ sequences, strongly suggest that the OMZ/CIZ boundary could represent a Cadomian suture that would reflect a major lithospheric discontinuity, allowing the weakness zone to be reactivated as a rift during Lower Paleozoic times and as flower structure during the Variscan orogeny.

[37] The PTFA might correspond to a transform fault related to the opening and closure of Rheic and (ephemeral) Paleotethys Oceans. These features are consistent with similar Cambrian to Devonian paleogeography between the (homologous) Central-Iberian and Central-Armorican zones, despite being located in opposed margins of Paleotethys [*Munhá et al.*, 1984].

[38] To the W of the PTFA transform fault, two paleogeodynamic reconstructions can be devised. On the first hypothesis [*Ribeiro et al.*, 2003], Paleotethys is a back-arc basin induced by Rheic subduction, leaving the Finisterra microcontinental plate (which could be continuous to the larger Moroccan Variscides) between both oceans. The second hypothesis is based on a modern analogue, represented by the strip of California to the west of the San Andreas Transform fault. In this case, there is no Rheic subduction and a minor ocean, Paleotethys (a branch of the Rheic), analogue of the Gulf of California, is separated from the main Rheic Ocean by a strip of continental lithosphere, corresponding to the Finisterra microplate; thus an intervening passive margin occurs on the northwestern side of PTFA, bounding the Rheic Ocean. Consequently, Finisterra is part of the Rheic plate (as Baja, W California is part of the Pacific plate), and has paleo-geographic affinities with OMZ, to which it represents a possible conjugate margin. A transform fault should separate this segment form the main Gondwana Continent toward the SW. In both hypotheses a small ocean is the root of the BAOC back-arc obducted ophiolites, whereas the internal oceanic klippen in OMZ (IOMZOS) are ophiolitic sequences originated from the main Rheic Ocean [*Fonseca et al.*, 1999; *Pedro et al.*, 2005]. It is worth noting that there is a fundamental difference between Iberian and Armorican transects, with CAT above the Paleotethys (obducted ophiolite) in NW Iberia and an obduction-subduction orogen in SW Iberia that does not involve continental collision, at least until the Middle-Upper Devonian (∼385–375 Ma). Nevertheless, in both hypotheses, the subduction process will cause afterward simultaneous closure of Rheic and the subordinate ocean above the subducting slab, such as Paleotethys and the BAOC small ocean basin in SW Iberia.

[39] The role of PTFA transform purposed here is at variance with other geodynamic scenarios [*Simancas et al.*, 2002], because in the present interpretation subduction polarity is everywhere centripetal, toward the inner part of IAA, leading to Rheic consumption until collision of Avalonia with the previously connected Iberian-Armorican assemblage; opposing subduction [e.g., *Simancas et al.*, 2002] polarities are restricted to the southern Armorican suture with Iberia being underthrusted below Armorica.

[40] At this point it should be noted that the width of the oceans involved in the Variscan cycle is still a controversial issue; indeed, paleomagnetic and paleobiogeographic [*McKerrow et al.*, 2000; *Robardet*, 2002, 2003] reconstructions on the paleolatitudes of Africa during Devonian-Carboniferous times are highly ambiguous. According to paleomagnetic interpretations, Armorica collides with Avalonia in Early Devonian times (allowing a wide Paleotethys Ocean between Armorica and Gondwana); whereas paleobiogeographical interpretations suggest that Armorica was close to Gondwana during Devonian and Carboniferous. On this problematic issue, the only hard evidence is that the development by progressive tightening of IAA [*Ribeiro et al.*, 1995] requires the indentation (Cantabrian indentor; [*Matte and Ribeiro*, 1975]) of Gondwana and Iberia; consequently, Armorica and Iberia were close to Gondwana during all the Paleozoic. This interpretation does not exclude either transform motion between Armorican and Gondwana assemblages, or the formation of Mediterranean-type oceans in a convergent context late in the Variscan cycle (as presently illustrated by the Alpine cycle between Eurasia and Africa).

[41] The two contrasting interpretations have significant implications on the timing of collision between different plates inside the Armorican assemblage and Gondwana, which may range from Early Devonian times to much later. There is no direct evidence to discriminate between both

interpretations because the collision zone between Armorica and Avalonia was strongly affected by the opening of the Atlantic along a transect between NW Iberia and Newfoundland; thick Meso-Cenozoic cover and high stretching of pre-Mesozoic basement preclude a reconstruction of the geodynamic evolution of this basement. Therefore an indirect approach should be tentatively essayed: given the IAA continuity, the timing for collision between Armorica and SW Britain (along N-S transects) and between Iberia and South Portuguese Terrane (across a NE-SW transect), must be investigated envisaging two main possibilities for possible diachronic collision events: (1) either an early collision took place within a scenario of narrow oceans, eventually slowing down plate convergence inducing considerable intracontinental deformation at low strain rate; or (2) assuming a wide ocean framework, gradually vanishing oceans can persist in until late stages of the Variscan cycle.

[42] The geodynamic evolution of the SW Iberian suture has strong implications in the lithosphere thermal regime through time. During back-arc extension, the expected high heat flow was caused by processes related to the lower plate hinge rollback in a steep (N-directed) subduction zone. Subsequent gradual decrease of the subduction angle and relative increase of the convergence rate, should have led to compression of the back-arc domain and, further, to the arc system overthrusting, decisively contributing to the thickening of the Iberian-Armorican assemblage. That is why the early, mafic calc-alkaline orogenic magmatism triggered by subduction (~360–370 Ma) is immediately followed by an event of intense magmatism either in the SPZ or in the OMZ southern border (~355–345); the latter recording the subduction blocking and subsequent (inferred) slab break-off [*Jesus et al.*, 2007]. Concurrently, the thermal effects related to widespread igneous activity coupled with the radiogenic heat provided by stacking of fertile upper crust lithologies over the Iberian-Armorican assemblage, supply the heat needed to sustain the observed LP-HT regional metamorphism and the initial stages of late-collision magmatism (quite often, involving mixing of mantle-derived and crust-derived melts). Gravitational/mechanical balance between crustal thickening and erosion processes near the SPZ-OMZ boundary suture, induced rapid crustal uplift at ~340 ± 5 Ma [*Jesus et al.*, 2007] and constrained subsequent regional heat flow regimes. This interpretation integrates coherently the available structural, petrological and geochemical data, being compatible both with the IBERSEIS results [*Simancas et al.*, 2003] and the deep electromagnetic imaging for the OMZ/SPZ lithosphere [e.g., *Pous et al.*, 2004; *Almeida et al.*, 2005, *Vieira da Silva et al.*, 2007]. Accordingly, the IBERSEIS Iberian Reflective Body interpreted by *Carbonell et al.* [2004] as a sill-like intrusion of mantle-derived rocks, may otherwise represent a conductive crustal layer (~15–20 km depth) that corresponds to a middle-crust décollement developed at the top of high-grade basement.

3.6. Upper Devonian to Westphalian-Stephanian Boundary (~350–300 Ma)

[43] Convergence on the IAA outer side continued during the Upper Devonian and Carboniferous until Westphalian–Stephanian times (Figure 10). In the SW Iberia transect, the passive SW margin abuts the convergent NE margin in Upper Westphalian, when flysch deposition within accretionary prism is replaced by molasse within the uppermost Westphalian and Stephanian intermountain basins. Geophysical data [*Lefort*, 1989; *Silva et al.*, 2000] suggests that the passive SW Iberian margin is part of Avalonia. In the SW England–Armorica transect the obduction/subduction orogen is followed by collision of Armorica and Avalonia in Upper Devonian times, approximately at the same time as in the SW Iberia traverse. In both transects, Avalonia is underthrust below Armorica/Iberia (already assembled by closure of Paleotethys) and dextral migration of the Finisterra continental plate are induced by dextral transpression of the main continental players (Gondwana, Laurentia, Baltica). The lower Avalonian plate is gradually bent around IAA and consequent extensional tectonics induced bimodal magmatism in SW Iberia generating the Pyrite Belt Volcano-Sedimentary Complex during Upper Devonian to Lower Carboniferous; oblique collision produced a transpressive tectonic regime [*Ribeiro et al.*, 1990], with strain partitioning leading to local transtension concentrated mainly in the Iberian Pyrite Belt. In SW England and Ireland, magmatism and hydrothermal activity also affected the lower plate margin and the foreland well to the N of the Variscan Front [*Dewey*, 1982; *Russell*, 1997]. These processes occur outside the context of subduction zone magmatism and simply reflect intraplate deformation coupled by intense and long-lived magmatism during the Variscan cycle.

[44] Rising of brittle-ductile transition due to rapid crustal uplift/erosion near the OMZ/SPZ suture resulted in significant reduction of crustal strength, favoring contamination and mixing of preexistent mantle-derived magmas (still residing in magma crustal chambers) and anatectic magmas (~330–325 Ma). The emplacement of the remaining late-collision granitoids (~315–330 Ma) and postcollision granites (~300–280 Ma, immediately above brittle-ductile mechanical transition) should occur at progressively shallower depths [*Pinto et al.*, 1987].

[45] The late-collision and postcollision igneous activity is also well represented in the OMZ northern border and all over the CIZ. This strongly suggests that an appropriate, large-scale thermal regime was maintained in the internal domains of the orogen by more than about ~30–35 Ma. Indeed, in these internal domains, the age of regional metamorphism and of most granite bodies [*Capdevila et al.*, 1973; *Pinto*, 1985a, 1985b; *Pinto et al.*, 1987] peaked between ~320 and 300–280 Ma, and rapid crustal uplift occurred at ~300 Ma [*Mateus et al.*, 1995; *Mateus and Noronha*, 2001; *Marques et al.*, 2002]. Considering the chemical characteristics of granites [*Bea et al.*, 1987, 1999; *Beetsma*, 1995; *Castro et al.*, 2000; *Neiva and Gomes*, 2001; *Dias*, 2001] and the structural control of their emplacement [*Ribeiro*, 1981], mechanisms other than radiogenic heating should be invoked to explain the vigor and the time span of that thermal regime. Possible heat sources include (1) convective removal of the thickened thermal boundary layer and (2) delamination (detachment) of the lithosphere mantle [*Houseman et al.*, 1981; *England*

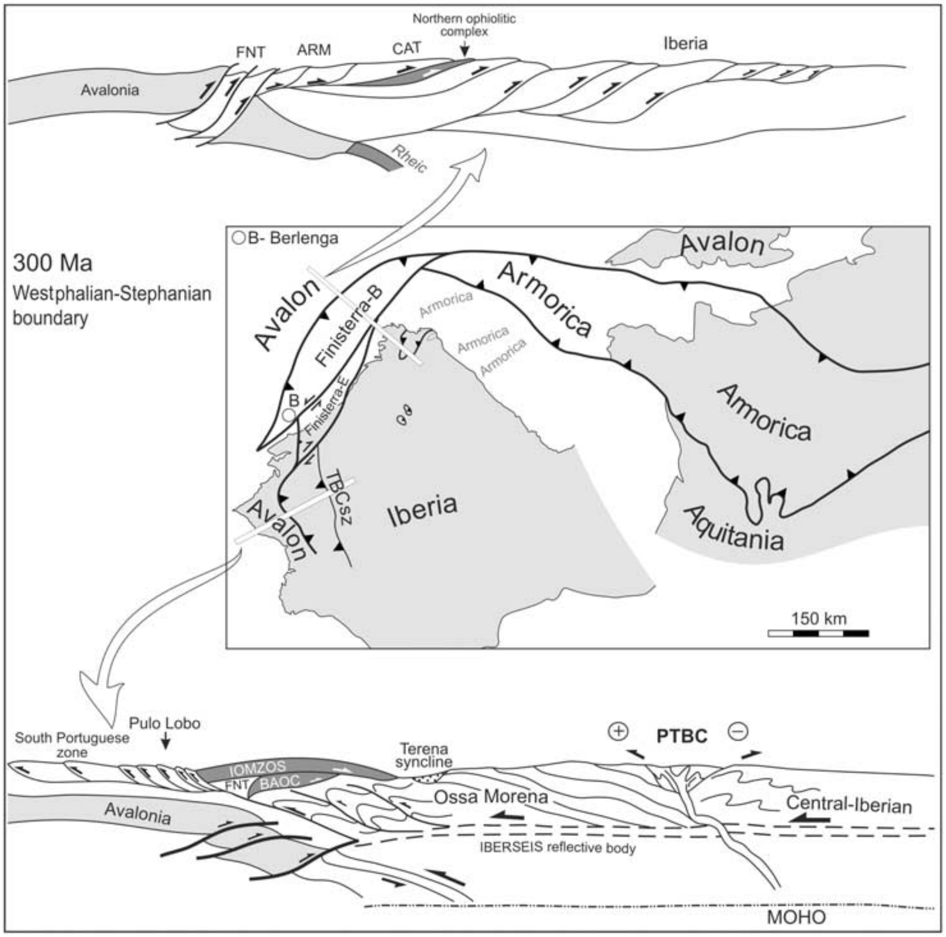

Figure 10. Paleogeographic reconstruction (300 Ma) of Avalonia-Armorica-Iberia/Aquitania, Finisterra, displaying Espinho (E) and Berlenga blocks (B), as well as Rheic, BAOC, and IOMZOS oceanic domains; reconstruction of NW Iberia-Armorica-Finisterra-Espinho and Finisterra-Berlenga-Avalonia transects and SW Iberia-IOMZOS-FNT-BAOC-Pulo do Lobo-South Portuguese Terrane and Avalonia transects.

and Houseman, 1989; *Platt and England*, 1993; *Schott and Schemling*, 1998]. Since the geological consequences due to these mechanisms are very similar it is virtually impossible to single out one.

3.7. Lower Permian (∼280 Ma)

[46] The Variscan Orogeny ends by continental dextral transpression between Laurussia (Avalonia) and Gondwana, closing the Ural Ocean toward the E and the Theic Ocean to the West [*Arthaud and Matte*, 1977]. In West Iberia, the Finisterra plate comprises high-grade metamorphic rocks and highly deformed granitoids outcropping in the Farilhões Islands (Berlengas archipelago, on the western offshore of Portugal; Figure 11). These geological formations are the only exposure of Variscan basement to the west of Lusitanian Basin, displaying characteristics that are similar those of the OMZ HT-LP metamorphic belts [*Moita et al.*, 2005a]. To the south and to the east of this archipelago, low-grade rocks similar to those typically found in SPZ were drilled (at ∼1.8 km and 2.5 km depth) in two holes performed in the Lusitanian basin, near Vila Franca de Xira (25 km NNE of Lisbon) and Bemfeito (45 km N of Lisbon), respectively; equivalent rocks were also dragged offshore to the south of Berlengas. On the basis of this information, coupled with geophysical subsurface data [*Silva et al.*, 2000], the Finisterra plate should be split in two blocks. The eastern block, extending westward of the PTFA dextral transform, is the Espinho domain [*Chaminé et al.*, 2003], showing a geological evolution alike of OMZ in the Iberian plate; the western block corresponds to the Berlengas domain, that is separated from the former block by a NNE-SSW sinistral shear zone, which is a intraplate conjugate of the PTFA transform. The overall tectonic pattern is similar to the western Himalayan Syntaxis [*Matte*, 1986], generated by progressive closure of the acute angle between conjugate ductile shear zones due to continued continent collision.

[47] An E-W compression affected the whole domain to the west of PTFA transform during post-Stephanian times, allowing strain accommodation in contemporaneous metasediments filling the Buçaco intramountain basin (Figure 11).

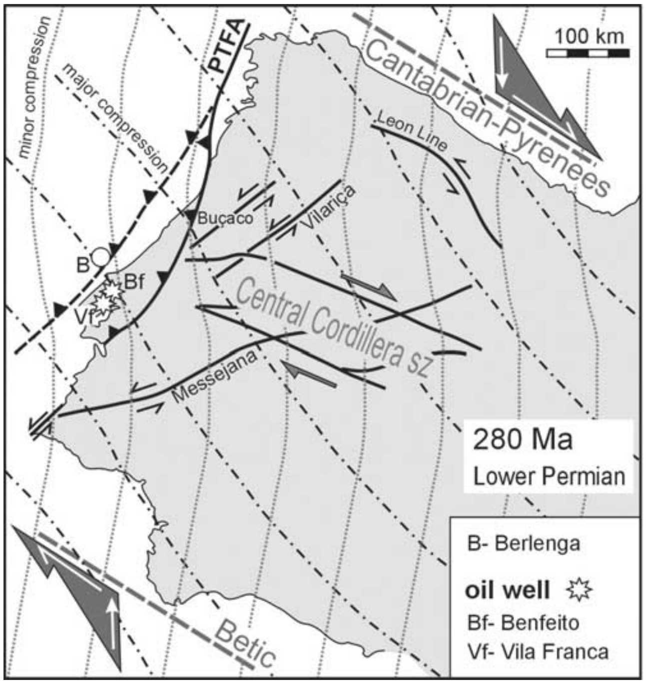

Figure 11. Major structures generated during Late Variscan (280 Ma) tectonic regime: dextral transform–Cantabrian, Pyrenees, and Central Cordillera shear zone; sinistral transform–Leon line; sinistral domains–Vilariça and Messejana Faults, Buçaco Basin (on the footwall of the Porto-Tomar-Lower Tagus Valley thrust to the E), and Berlenga thrust zone to the east. Reconstruction of Variscan basement within the (Mesozoic) Lusitanian Basin is based on both direct exposures and drill core data (B, Berlenga Island; Bf, offshore oil well; Vf, onshore oil well). Stress trajectories of major and minor compressive stress according to Cosserat generalized continua theory.

In the Berlengas Island, a 280 Ma granite [*Priem*, 1965] was affected by reverse faulting to the east across gently dipping N-S fault zones that preserve features developed near the brittle-ductile transition; these faults reflect reactivation of early sinistral ductile shear zones at the boundary between the Berlengas and Espinho blocks of the Finisterra Plate. The E-W compression was therefore more intense in the W boundary of the Iberia Peninsula mainland; this explains why Permian sediments are restricted to basins in Eastern Iberia, mostly in Spain [*Vera*, 2004].

[48] In the Iberia Peninsula mainland, to the east of PTFA shear zone, Late-Variscan tectonics [*Arthaud and Matte*, 1977; *Marques et al.*, 2002] was expressed by development of variable transpressional structures, inducing constriction. Dominant strain corresponds to an E-W movement between E-W major dextral shears parallel to the transform motion along the northern (Cantabrian-Pyrenees deformed belt) and southern (Betic deformed belt) boundaries of the Iberian Block. An E-W dextral shear zone developed in the basement of the Central Cordillera [*Ribeiro*, 2002]. NNE-SSW sinistral strike-slip faults (Vilariça-Messejana system) are formed in the brittle-ductile transition [*Mateus*, 1995], corresponding to "dominos" relative to the main E-W dextral system [*Ribeiro*, 2002]; these structures nucleated in tension fractures of previous ductile structures such as antiforms [*Mateus*, 1995] and propagated by reactivation of previous dextral ductile shear zones of the Upper Carboniferous stage [*Marques et al.*, 2002]. More localized structures can form in response to N-S (intermediate) compressive stress. Paleomagnetic data [*Weil et al.*, 2001] suggests the generation of an almost complete secondary arc at the E-W branch of Cantabrian arc (south of Leon Line) in the Lower Permian. E-W folds also form at the tip of NNE-SSW sinistral strike-slip faults such as the Amêndoa-Carvoeiro Synform [*Romão et al.*, 1997; *Romão*, 2000]. The Porto-Tomar Fault Zone is curved (with convexity to the E) as a consequence of this transpressive regime; SW of Tomar the lower Tagus Fault Zone nucleated in the former Rheic suture and propagated southward (Figure 11).

[49] A pure transform type movement along Cantabrian-Pyrenees and Betic major shears would result in a straight N-S (to the E) thrust at the border of Iberia; however, the curvature of this boundary reflects a secondary N-S compressive motion in the constrictive transpressive regime. Kinematic reconstructions suggest less cumulative displacement in the N-S shortening direction than in external rotation of "dominoes" bounded by the NNE-SSW sinistral strike-slip faults induced by the major E-W shortening direction [*Ribeiro*, 2002]. The implications of this tectonic regime on the evolution of IAA will be discussed below.

[50] The proposed Lower Permian kinematic regime is compatible with the Euler Pole of rotation for Gondwana and Laurussia motion [*Dewey*, 1982] at that time, reflecting intracontinental deformation after final collision between continental players. The transpressive regime is a consequence of the nature of convergent triple junctions in the southern tips of Urals and northern tip of Southern Appalachians, which are connected by a transpressive transform through the European Variscides [*Arthaud and Matte*, 1977]. Therefore the complete mechanical interpretation of domino style of distributed deformation must be addressed through generalized continua theory (such as Cosserat Continua [*Figueiredo et al.*, 2004]), or continuum micropolar theory [*Twiss and Moores*, 1992]; both are more appropriate than classical continua theory to describe the schizosphere behavior [*Ribeiro*, 2002] in presence of significant instability.

[51] Following the Lower Permian compression, stress relaxation promoted extensional magmatism that is represented both by rhyolitic tuffs occurring below Triassic red beds (recognized in offshore oil drilling cores) near Berlengas, as well as E-W felsic dykes [*Ferreira and Macedo*, 1979] in the Iberian mainland block; these stress relaxing episodes represent the last manifestations of the Variscan orogeny.

4. Discussion: Geodynamic Evolution of the SW Europe Variscides and the Typology of Orogenic Belts

[52] The tectonic setting of the two transects depicted in previous figures for Iberia reflect different orogenic typologies in terms of Plate tectonics processes [*Sengör*, 1990].

The NW Iberia-Armorica transect depicts a continental-override collision type orogen; the Armorica plate is thrusted over the Iberian Plate by closure of a minor ocean, Paleotethys. The SW Iberia transect represents a noncollisional override type orogen by subduction of the (main) Rheic Ocean (below Iberia) until collision with Avalonia plate, underthrusting Iberia. Differences between the two orogenic regimes mainly reflect the fact that the intervening continental Armorica plate (between Rheic and Paleotethys) is preserved in the NW Iberia-Armorica transect, but ends against the PTFA shear zone, becoming reduced to narrow microcontinents (the Finisterra blocks) in the SW Iberia transect. The observed contrasts between continental-override and non-continental-override collision orogenic regimes gives further support to *Sengör*'s [1990] orogenic typology and are well represented in both transects; indeed, they depend ultimately on the width of the oceans involved in the Wilson cycle for each orogenic type: small for continental-override and large for non-continental-override collisions type orogens. Moreover, the width of the intervening continent between (major) Rheic and (minor) Paleotethys Oceans is also an important factor controlling the typology of collision belts. In the NW Iberia–Armorica traverse the intervening continent was quite wide; it resisted subduction and overrode the opposing continent on the other side of Paleotethys. The final result is the continental collision overriding of Iberia by Armorica. In the SW Iberia traverse the intervening continent, Finisterra, is narrow; most of it was subducted below Iberia, despite of the fact that remnants of the Rheic-Paleotethys oceanic lithosphere and minor slices of Finisterra arc were antithetically obducted on Iberia. The general tectonic regime is in accordance with flake geometry for the suture between Iberia (on the proximal Gondwana side of Paleotethys) and Finisterra (on the distal Gondwana side of Paleotethys).

[53] As an alternative to the previous interpretation, the different tectonic styles in the NW and SW Iberian transects may be due to distinct collisional orogeny boundary conditions. Moreover, this alternative interpretation is compatible with the previous one. Indeed, the general transpressive dextral regime that characterizes the Variscides may result from synchronous dominant-frontal collision in NW Iberia (by closing wider oceans) and dominant-oblique collision in SW Iberia (by closing narrower oceans); the subsequent kinematics induced strain portioning across the Ibero-Armorican Arc, leading to a prevailing thrust component in NW Iberia and prevailing strike-slip component in SW Iberia.

[54] Available syntheses for Central and Eastern Europe [*Matte*, 2002; *Franke*, 2000; *von Raumer et al.*, 2002] allow correlations with SW (Iberia) European Variscides. Main discrepancies on interpretations rely on the significance of the high-pressure–high-temperature assemblages that occur in NW Iberia CAT. Different ages and tectonic settings have been reported for these units: suture rocks of Eovariscan age [*Matte*, 2002]; record of Rheic subduction under the leading edge of Armorican assemblage at ~500 Ma [*von Raumer et al.*, 2002]; or rift related assemblages due to Armorica-Avalonia splitting at ~500 Ma [*Franke*, 2000]. Field relationships observed in CAT relics preserved in the Bragança Massif show that a previous high-pressure–high-temperature granulitic/eclogitic assemblages of Cadomian age (delineating a probable suture inside this orogen) was subject to rifting at 500 Ma [*Marques et al.*, 1992, 1996]. This is still a critical/debatable issue in Variscan geology that must be settled by further investigations across the orogen.

[55] Variscan sutures have been recognized in different segments of Paleozoic massifs separated by younger Basins, as well as the Tethys and Atlantic Oceans [*Franke*, 2000; *Matte*, 2002]; these features are particularly significant in what concerns the major Rheic suture between Armorica and Avalonia. The number of minor oceans and respective sutures inside the Armorican assemblage increase from SW to Central and Eastern Europe with consequent increasing tectonic complexity. Indeed, Paleotethys and, possibly, other minor oceans should have open from east to west [*Stampfli and Borel*, 2002]; therefore some of the micro plates may have been bounded by active transforms toward the west (resulting in a smaller number of ocean basins) as exemplified by the PTFA transform boundary between Armorica and Iberia. From central Europe to Armorica, Iberia, and Gondwana the oceans should have became narrower owing to role of transform systems parallel to PTFA, involving Iberia, the Moroccan Variscides and the main Gondwana continent [*Matte*, 2001].

[56] In the Moroccan transect [*Simancas et al.*, 2005] the main Rheic suture should be located to the east of the present outcrops of Variscan basement, terminating toward the west as part of the Avalonian plate. Some peculiar features of the Variscides, the width of the deformed belt, the dominant heat regime, and the plan view of the orogen, which have been used to individualize a "Hercinotype" orogen by opposition to the "Alpinotype" orogen [*Zwart*, 1967], were already addressed in the SW European sector by *Ribeiro* [2000] and *Ribeiro and Sanderson* [1996]. From these studies it may be inferred that the narrow width of Variscan oceans (with the exception of Rheic) played a crucial role in the geodynamic evolutionary features of Variscan type orogens. A modern analogue should then be searched in the Mediterranean Sea rather than in the Western Pacific [*McKerrow et al.*, 2000].

[57] High heat flow in the Armorican assemblage during the whole orogenic cycle is typical of the Variscides [*Ribeiro*, 2000], as recorded by extensive preorogenic and synorogenic granitoid magmatism, as well as widespread low-pressure metamorphism. *Crowley et al.* [2000] favor a plume controlled mechanism (favoring active rifting) for the genesis of the high heat flow anomaly during the preorogenic stage that was further sustained by subsequent collisional slab break-off and later lithospheric delamination (see above).

5. Conclusions: Three-Dimensional Geodynamic Evolution of the SW Europe Variscides

[58] The Variscides tectonic style is clearly distinct from Alpinotype orogens. The rationale for relating the character-

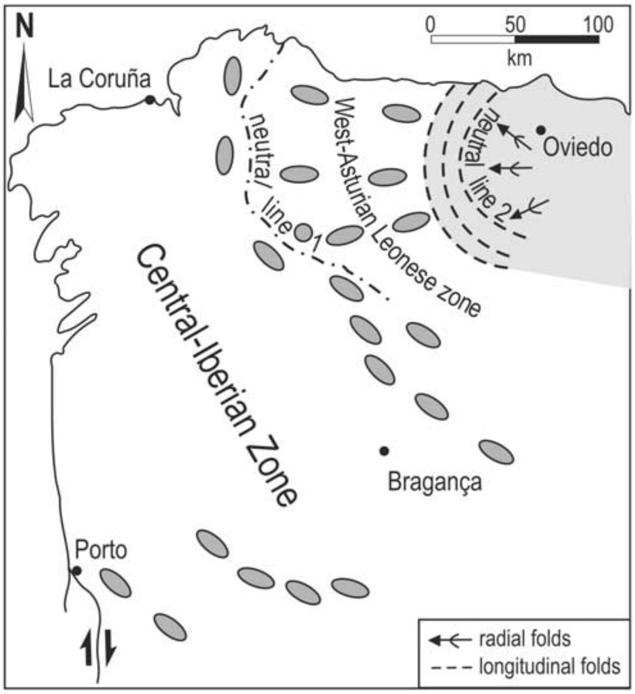

Figure 12. Deformation and internal strain in the Ibero-Armorican Arc. Structures developed during the thick-skinned stage involved longitudinal stretching in "b" kinematics axis, neutral line 1, with pure flattening and radical stretching in "a" kinematics axis. Structures developed during the thin-skinned stage are restricted to the Cantabrian Zone, with longitudinal folds, neutral line 2, and radial folds. Data are from *Ribeiro* [1974], *Matte and Ribeiro* [1975], *Pérez-Estaún et al.* [1980], *Ribeiro et al.* [2003], and *Gutiérrez-Alonso et al.* [2004].

istics of ocean basins to the orogens they generate by closure rely on the lithosphere rheological evolution during the entire Wilson cycle. A wide, high-spreading rate ocean is expected to result in a narrow orogen, whereas a narrow low-spreading rate ocean should produce extensive intraplate deformation outside the suture resulting in a wide orogen [*Kuznir and Park*, 1986]. Indeed, old subduction processes only leave a faint geological record at the surface, whereas obduction and collision processes (particularly, if involving numerous micro-plates) provide substantial tectonic memory of intraplate and interplate deformation.

[59] In the case of Variscides, slow opening of small ocean basins induced by mantle plume(s) led to a wide orogen with substantial intraplate deformation. Under this perspective, the plan view of the Variscan orogen allows the reconstruction of its 3D picture. In this respect, the arcuate picture of the Variscan belt contrasts with the linearity of other orogens, such as the Caledonides, reflecting the collision geometry/kinematics of the involved plates, with the Alpine chain as a modern analogue [*Matte and Mattauer*, 2003].

[60] The perspectives presented in this paper for the genesis of the IAA were summarized in previous publications [*Pérez-Estaún et al.*, 1988; *Ribeiro et al.*, 1995; *Dias and Ribeiro*, 1995] and tested against 3-D strain distribution [*Ribeiro et al.*, 2003]. The views presented here differ from other published interpretations in two main issues. The first one concerns the role of the Cantabrian indentor as a promontory of Gondwana; this hypothesis was recently discarded by considering an Avalon indentor in the SW Iberia-Morocco sector [*Simancas et al.*, 2005]. Our analysis favors the previous solution because an Avalon indentor is incompatible with the arc parallel stretching; this is indicated by a **b** kinematic axis in the front of the Cantabrian indentor, which is preserved in both the high-grade rocks of the allochthonous complexes and the low-grade autochthon of CIZ. The second issue concerns the arc generation by orocline bending [*Gutiérrez-Alonso et al.*, 2004] in late to postorogenic times (295–285 Ma); 3-D strain distribution analysis along the entire IAA is not compatible with this explanation rather implying a progressive arcuation, as quoted above from pre to late orogenic stages (at least from ~500 Ma to 285 Ma). Indeed, two main stages of the arc generation must be distinguished (Figure 12). An early stage (Figure 13a) of thick-skinned orocline bending is represented in the internal zones where arc-parallel stretching (overprinted by centripetal stretching parallel to transport direction in allochthonous units) is clearly early syn-orogenic; in the autochthon, the arc parallel stretching is also coeval of the first cleavage, defining together an early to syn-orogenic diachronic plane-linear fabric that range in age from ~395 Ma in the W Upper Allochthonous to ~320 Ma in the eastern WALZ [*Dallmeyer et al.*, 1997]. The ductile strain define (Figure 12) a neutral fiber along the eastern flank of the "Ollo de Sapo" antiform, near the CIZ-WALZ boundary (for further details, see *Ribeiro* [1974, Figure 59, p. 253]) between an outer arc with tangential stretching and an inner arc with radial stretching, providing evidence for arcuation by tangential longitudinal strain or orthogonal flexure [*Ribeiro*, 1974]; these features are shared by both deep crustal rocks involved in the Variscan orogeny and pre-Variscan basement, suggesting orocline bending for the secondary arc generation component. A second stage (Figure 13b) of arc generation is restricted to the platform cover of the Cantabrian Zone that starts to deform diachronously in the time interval 320–310 Ma [*Dallmeyer et al.*, 1997]. According to paleomagnetic data [*Weil et al.*, 2001], this event represents a thin-skinned secondary arcuation that reinforces the inner arc curvature relative to the previous outer arc segment in the CIZ and WALZ; orocline bending should be excluded because it is not compatible with the weak ductile strains observed in the Cantabrian Zone [*Pérez-Estaún et al.*, 1988]. In the Cantabrian Arc, a neutral fiber is also developed between an outer arc in the Narcea tectonic window, and an inner arc with conic radial folds, in the Somiedo Nappe domain [*Gutiérrez-Alonso et al.*, 2004]; this arc was generated by brittle deformation mechanisms with differential displacement in the nappe pile of the Cantabrian Zone [*Pérez-Estaún et al.*, 1988]. In our interpretation a constrictive transpressive regime results in a major E-W compression and minor N-S compression in the cover above a basal décollement on top of a quasi-rigid

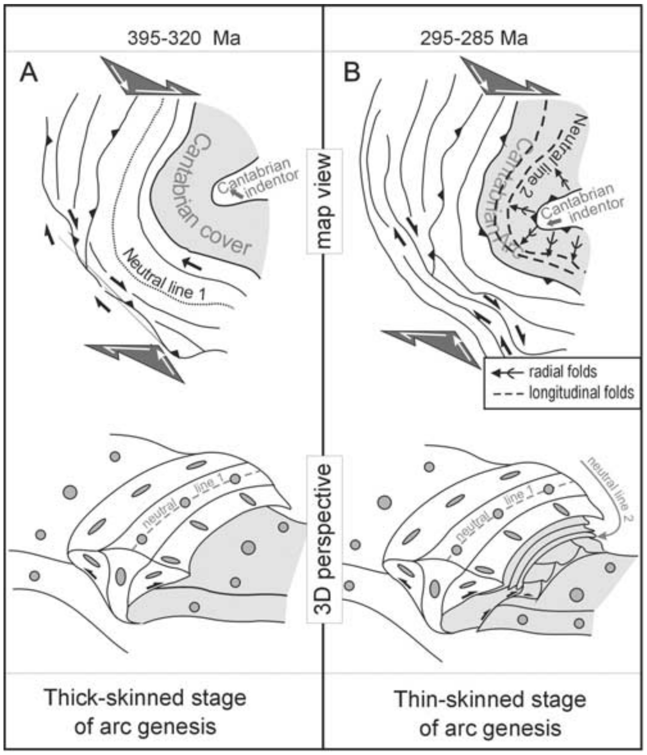

Figure 13. Evolving tectonic regimes of the Iberia-Armorican Arc by movement of the Cantabrian indentor in two stages (shown in map view and 3-D perspective). (a) Thick-skinned regime (395–320 Ma) in west of Cantabrian zone cover. (b) Thin-skinned regime (295–285 Ma).

Cantabrian indentor (that moulds the boundary of this indentor), involving a mechanism that is similar to that in the western Alpine arcs [*Lickorish et al.*, 2002]. This hypothesis is also consistent with data on Late-Variscan evolution (∼280 Ma; see section 2.7), but requires further testing against geophysical data on the anisotropy of Variscides deep structures.

[61] The rotation of plates with sinuous boundaries requires the presence of a component of frontal collision at the head of promontories. Regarding the Variscides, a global regime of dextral transpression between Laurussia and Gondwana explains quite well the IAA development by increasing displacement and shortening around the Arc, as Iberia moves clockwise relative to Armorica [*Pérez-Estaún et al.*, 1988; *Ribeiro et al.*, 1995; *Dias and Ribeiro*, 1995].

[62] Despite the common fundamental processes involved in orogenesis, each mountain chain has its own singularities; the Variscides are no exception to the universality of laws and variability of boundary conditions. Thus it is worth to examining the inferences from the SW European Variscides palaeo-orogen in order to assess possible implications on the driving mechanism of plate tectonics.

[63] It is a matter of discussion if lithosphere drives plate tectonics from the top [*Anderson*, 2001] or if lithosphere resists plate motion caused by astenospheric viscous flow [*Molnar*, 1988]. Evidence from geophysics and geodesy is indirect because it is impossible to observe what really happens at depth. However, old orogenic belts allow continuous observations on the kinematics from the schizosphere through the plastosphere and the astenosphere. It is considered [*Scholz*, 2002] that the lithosphere is divided into an upper, brittle schizosphere and a lower, ductile plastosphere. The brittle-ductile transition is located slightly below the base of the seismogenic layer; thus it has an alternating behavior of coseismic dynamic slip and interseismic semibrittle flow, which grades to complete ductile behavior at the top of the plastosphere.

[64] Astenospheric relics may be exposed in ophiolite sequences and detailed studies in well preserved ophiolite complexes [*Nicolas*, 1989] indicate that the astenosphere drags the lithosphere. However, the mechanism involved in continental settings is not clear, because the astenosphere/lithosphere boundary is not exposed. The problem must be addressed in relation to the driving mechanism for arcuate mountain belts, such as the IAA. In the interpretation favored in this paper, the IAA is due to dextral transpressive shearing between Laurussia and Gondwana. A promontory of Gondwana was then affected by subduction followed by continental collision. As already mentioned, the IAA shows variable stretching (Figure 14), parallel to the arc in the outer sectors and almost perpendicular to it in the inner domains where it becomes subparallel to centripetal nappe transport; this pattern was due to secondary arcuation imprinted in primary arcuation. Centripetal nappe transport to SE (in present geographical coordinates) due to collision,

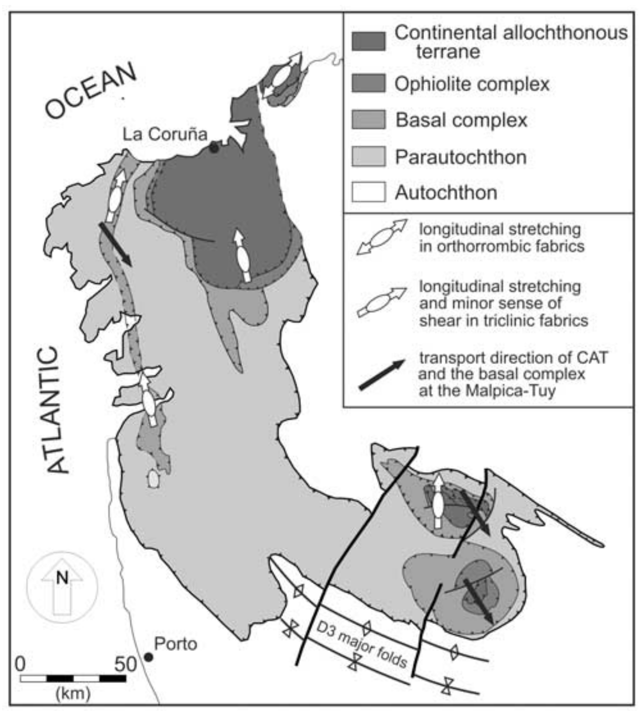

Figure 14. Early ductile structures in the thick-skinned outer Arc of NW Iberia. Major tectonic units (CAT, OPH, BC, PA and A: see text) and ductile lineations.

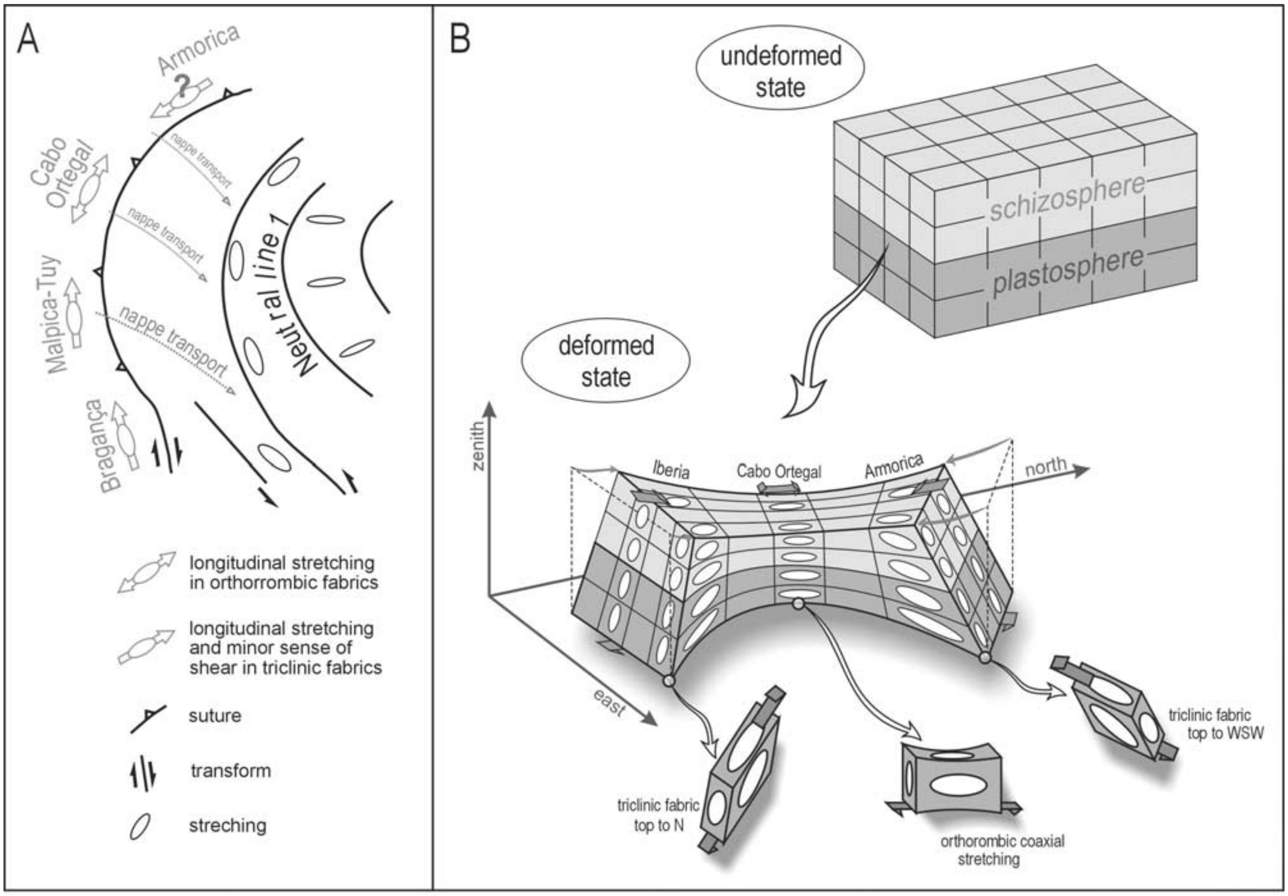

Figure 15. Interpretation of 3-D ductile strains in Ibero-Armorican Arc (IAA). (a) Schematic map view of IAA, displaying the generation of longitudinal structures along the arc and centripetal transverse structures related to nappe transport. (b) Reference grid for underformed state and deformed grid for lithosphere (upper schizosphere and lower plastosphere).

produces monoclinic structures at all scales that obliterate arc parallel stretching generated in the allochthonous units of the earlier subduction stage. Arc parallel stretching in the allochthonous is less curved than the major (earliest) structures in the autochthon; this observation implies that stretching was produced in the root zone of the NW Iberia allochthonous before their emplacement at present location (Figure 15a). Coeval with early arc parallel stretching, minor secondary shear to the N (Figure 15b), in the Basal Complex of Malpica Tuy [*Llana-Fúnez*, 2002; *Llana-Fúnez and Marcos*, 2002] and Ordenes, as well as in the Bragança CAT [*Marques et al.*, 1996], grades to coaxial stretching and produces orthorhombic (micro- and meso-scale) fabrics at the maximum curvature zone of the lineation in the Cabo Ortegal CAT [*Fernández*, 1993]. These relationships suggest that the schizosphere is dragged by the plastosphere [*Ribeiro et al.*, 2003], because the sense of nappe transport direction to SE has a component which is opposed to the triclinic fabrics (minor) shear component to the N (Figure 15b). Channel flow in the lower crust may be a viable mechanism for dragging the schizosphere by the plastosphere. This mechanism is consistent with the inferred PT paths of exhumed rocks in NW Iberia, being supported by theoretical [*McKenzie and Jackson*, 2002] and numerical modeling [*Henk*, 2000], as applied to both the Variscides [*Franke and Stein*, 2000] and the Uralides [*Brown and Juhlin*, 2006]. Nevertheless, since the plastosphere-astenosphere boundary is not exposed this process cannot be demonstrated beyond doubt; it remains to be solved if the whole lithosphere is dragged by the astenosphere with a constant shear sense, or if the plastosphere has a channel type profile, inducing an opposite shear sense from top to base. Field data is compatible with bottom up tectonics, but cannot be used to infer either plastospheric channel flow or astenospheric dragging of the continental lithosphere.

[65] It should be noted that these considerations only apply to the W Cantabrian thick-skinned ductile segment, where deep crustal rocks are affected by arc generation and there is direct evidence for the driving mechanism for arc generation. The same model can be applied to the Bohemian Arc [*Matte and Mattauer*, 2003], toward the eastern termination of the Variscan Fold Belt. The indenter moves to NE (in present geographic coordinates), but the stretching lineation preserved in klippen (rooted in the inner zones

of the indenter) on NW side of Bohemia show a shear component to SW, at high angle to thrust transport to NW [*Franke*, 2000]. Thus inferences from tectonics of old orogens can be confronted with geophysical and geodetic data of active orogens [*Park and Levin*, 2002; *Mattaeur*, 2002], which display a complete range of situations from ridge normal flow through subduction parallel flow to trench parallel extensional flow. In active subduction and collision orogens, seismic anisotropy of the upper mantle can be mapped and if these orogens are arcuate (Caribbean, Scotia and Banda); the arc generation may be monitored by geodesy and connected to dynamics of the mantle below.

[66] From the comparative analysis of SW Variscides paleo-orogen a contribution to the fundamental question posed above ("do the plates drive mantle flow or does the mantle drive the plates?") may be conceptualized as follows. The plates should organize mantle flow because they are an integral part of the convective system [*Davies and Richards*, 1992]. Indeed, the evidence gathered from old orogens indicates that the whole elastic schizosphere is driven by viscous plastosphere, whereas its singular units (bounded by active faults) are connected in a fractal network, such that they can influence the kinematics of the underlying plastosphere by a feedback top-down mechanism [*Ribeiro*, 2002]. Therefore modern "soft plate tectonics" can explain the Variscides and may be generalized to the whole Phanerozoic, as well as to Proterozoic times [*Ribeiro*, 2002]. Plate rigidity will increase, as the plate driving mechanism will inexorably slow down.

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